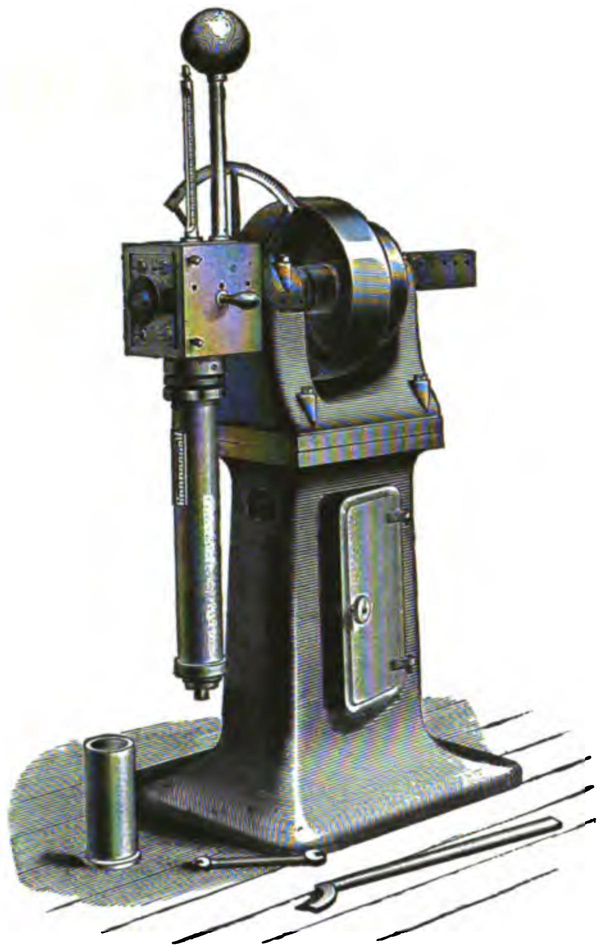

THE RAILROAD LUBRICANT-TESTING MACHINE.
[As built by the Pratt & Whitney Co.]

A TREATISE

ON

FRICTION AND LOST WORK

IN

MACHINERY AND MILLWORK.

BY

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G. F.

TO

THE ENGINEER, PHYSICIST AND MATHEMATICIAN

G. A. HIRN,

ONE OF THE EARLIEST WORKERS IN THIS FIELD,

This Little Work

IS INSCRIBED, IN GRATEFUL APPRECIATION OF PERSONAL, AS WELL AS OF PROFESSIONAL, AID AND ENCOURAGEMENT, AND IN RECOGNITION OF A MOST STIMULATING EXAMPLE OF NOBLE WORK, INSPIRED BY NOBLER THOUGHTS AND NOBLEST AIMS.

PREFACE.

THE following pages contain the results of an attempt to exhibit the facts and laws involved in the waste of energy by friction in machinery and mill-work. It is readily seen that in all well-designed machinery friction is the sole cause of lost work. The other possible cause, the permanent deformation of parts, cannot in such cases exist: every piece which is altered in shape by the forces received and transmitted, since it is never sprung beyond the elastic limit, restores by its restoration of form all energy expended in its alteration. Hence, the study of the methods and magnitudes of friction-losses, and the laws governing their production, is, next to the theory of pure mechanism, the most important study in relation to the transmission of energy by machinery.

In the endeavor to reconcile the facts of common experience with the data supplied by the working library of the engineer, and in the attempt to secure additional essential experimental data relating to lubricated surfaces, the Author was led into a series of investigations which revealed new facts and established the inapplicability of the usually received values of the coefficients of friction to much of the most familiar work of the engineer. The enormous variations observed in their values, as produced by change of pressure, of speed, and of temperature, and revealed by such investigations, compelled the Author to devise new apparatus and new methods of experiment, and finally led to the accumulation of a large mass of new and practically applicable data, the most important of which may be found here published.

To make the work complete, it has been attempted to exhibit, as concisely as possible, the principles involved in the transmission of power and the performance of work, and in the waste of power by friction. It has also been attempted to show what are the methods of reducing such wastes, how to determine the purity and the intrinsic values of the unguents, and finally to ascertain how and to what extent variations of the magnitudes of these wastes are produced by variations of the conditions affecting the machinery exhibiting them.

A large proportion of the work consists of new matter containing new data obtained by new investigations, and exhibiting variations from the formerly accepted laws of friction by new methods. Of this new matter a part has been published in an earlier work,* which contains the substance of lectures given by the Author before the Master Car-builders' Association and elsewhere. The present work is much more extensive, and in it the endeavor has been made to bring the subject fully up to date. The last chapter, which treats of the real value of lubricants, contains a development of principles enunciated in the earlier work, but never before fully worked into a consistent algebraic theory, with illustrations of its practical application.

The experience and observation of the Author during a quarter of a century of work in the mechanical branches of engineering, in the design and practical construction and in the management of steam and other machinery, have impressed upon him the necessity of the study by the engineer of the nature, causes, and remedies, of lost work in mechanism, so strongly, that his expression of such views as are here presented may sometimes appear to give an exaggerated idea of the importance of this division of the subject; but in his opinion it would be very difficult to impress this matter too strongly upon the mind of the student or of the young engineer.

It is his hope that the following pages may prove valuable

* Friction and Lubrication. Railroad Gazette Publication Co., New York, 1879. 12mo, pp. 212.

to the student, to the practising engineer, and to the man of science. The book is planned with a view to its use both as a text-book and as an office hand-book.

The Author is greatly indebted to his colleagues, Professors Albert R. Leeds and C. A. Carr, U.S.N., for their kindness in assisting him in reading proof-sheets.

Stevens Institute of Technology,
Hoboken, N. J., April, 1885.

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FRICTION AND LOST WORK.

CHAPTER I.

THEORY OF MACHINERY—ITS ACTION AND ITS EFFICIENCY.

1. **The Object of all Mechanism** is to produce a certain definite motion of some part or parts—the position and form and the methods of connection of which are known and fixed—against any resistance that may be met with in the course of such movement. This operation is also usually effected by utilizing the action of some other piece of mechanism which is itself a "prime mover," or is driven directly or indirectly by a prime mover, such as a steam-engine or a water-wheel. Every machine and every train of mechanism is therefore a contrivance by means of which energy or power available at one point, usually in definite amount and acting in a definite direction and with definite velocity, is transferred to other points, there to do work of definite amount, and there to overcome known resistances with known velocities.

The object of the engineer in designing mechanism is to effect this transfer of energy and these transformations at the least cost and with least running expense, and hence with maximum efficiency of apparatus. It is often important to secure minimum volume and weight of machine, as well as maximum effectiveness in operation.

2. **The Work of a Machine** is measured by the magnitude of the resistance encountered and the velocity with which it is overcome. The nature of the work, aside from its simple kinetic character, is as widely variable as are the details of human industry.

Prime Movers are those machines which receive energy directly from natural sources, and transmit it to other machines which are fitted for doing the various kinds of useful work. Thus, the steam-engine derives its power from the heat-energy liberated by the combustion of fuel; water-wheels utilize the energy of flowing streams; windmills render available the power of currents of air; the voltaic battery develops the energy of chemical action in its cells; and, through the movement of electro-dynamic mechanism, this energy is communicated to other machinery, and thus caused to do work.

Machinery of Transmission is used in the transformation of energy supplied by the prime mover into available form, for the performance of special kinds of work, or for simple transmission of power from the prime mover to machines doing that work.

The work to be done may be the raising of weights, as in hoisting and pumping machinery; the transportation of loads, as on the railway or in the steamship; the alteration of the form of solid masses, as in machine-tools; the overcoming or even the utilizing of frictional resistances, as in brakes; or any other of the numberless operations performed in mills and factories by machinery.

Machines and *Machine-tools* receive energy, derived originally from prime movers, and transferred to them through machinery of transmission, and apply that energy to special kinds of work to which they are precisely adapted by their design and construction. Thus, looms apply such energy to the weaving of cloth; lathes are especially fitted for the production of parts having circular sections; planing-machines produce straight-lined surfaces.

3. **The Power demanded by a Machine** is that needed to do the work for which the machine is designed, plus the additional amount expended by the machine itself, in transferring the first-mentioned quantity from the source of power to which the machine is connected, by transmitting mechanism to the point at which the work is to be done. Where the machine is subject to shock and jar sufficient to permanently distort its parts, or the bearing surfaces, a portion of the power demanded

is wasted in doing this work; where the journals heat, considerable amounts of energy are sometimes lost as heat-energy: in all cases some loss occurs in this way. Where power is transmitted by the expansion and compression of elastic fluids, also, energy is often lost in large amounts by transformation into heat.

The power demanded by any machine thus always exceeds that expended by the machine upon its proposed task. Were these wastes not to occur, the power transmitted would be the same in amount at every point in the machine.

4. **Work**, as a term in the science of engineering, may be defined as that action by which motion is produced against the resistance continuously or intermittently opposed to any moving body. It is measured by the product of the direct component of the resistance into the space traversed. Where the resistance is variable, its mean value is taken. Thus, if R be the resistance and S the space, the work is, for constant resistance,

$$U = RS, \quad \ldots \ldots \ldots \quad (1)$$

in which U is measured in foot-pounds or kilogrammetres. For a variable resistance, R, acting through a space, s,

$$U = \int Rds, \quad \ldots \ldots \ldots \quad (2)$$

which can be integrated when R is known as a function of s.

Resistances, and the forces by which they are overcome, are measured by engineers, usually, either in British or in metric units, as the pound or the kilogramme. Work, and the energy expended in doing work, are thus both measured by the product of the pounds or the kilogrammes of resistance or of effort into spaces of which the measure is usually given in feet or in metres. The unit of work and of energy is thus either the foot-pound or the kilogrammetre.

The British and metric measures have definite relations, which are given in tables to be found in all engineers' table-books.

Where the motion of the machine or of the part doing work is circular, the space traversed may be measured by the angular motion, a, multiplied by the lever-arm, l, and their product, multiplied by the force, R, exerted, gives the measure of the work done. Thus:

$$\left.\begin{aligned} U &= aRl \\ &= 2\pi nRl; \end{aligned}\right\} \quad . \quad . \quad . \quad . \quad . \quad . \quad (3)$$

in which last expression n is the number of revolutions made in the unit of time.

These values are equivalent to the product of the angular motion into the moment of the resistance.

Work may also be measured, as in steam, air, gas, or water-pressure engines, by the product of the area of piston, A, the mean intensity of pressure upon it, p, the length of stroke of piston, l, and the number of strokes made. Thus,

$$\begin{aligned} U &= Apln \\ &= Aps \\ &= pV, \end{aligned} \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad (4)$$

when V is the volume of the working cylinder multiplied by the number of strokes; in other words, the volume traversed by the piston.

Where the force acting, or the resistance, acts obliquely to the path traversed, it is evident that only the component in that path is to be considered.

Diagrams exhibiting the amount of work done and the method of its variation are often found useful. In such diagrams the ordinate is usually made proportional to the force acting or to the resistance, while the abscissas are made to measure the space traversed. The curve then exhibits the relations of these two quantities, and the enclosed area is a measure of the work performed. With a constant resistance, the figure is rectilinear and a parallelogram; with variable velocities and resistances, it has a form characteristic of the methods of operation of the part or of the machine the action of

which it illustrates. In the first case, the area can be obtained by multiplication of the difference of the ordinates by the difference between maximum and minimum abscissas; in the second case, it may be obtained by any convenient system of integration, of which systems that of mechanical integration, as by the "planimeter," is usually best.

5. **Power** is defined as the *rate of work*, and is measured by the quantity of work performed in the unit of time, as in foot-pounds or in kilogrammetres, per minute or per second. The unit commonly employed by engineers is the "horse-power," which was defined by Watt as 33,000 foot-pounds per minute, equivalent to 550 per second, or 1,980,000 foot-pounds per hour. This is considered to be very nearly the amount of work performed by the very heavy draught-horses of Great Britain; but it considerably exceeds the power of the average dray-horse of that and other countries, for which 25,000 foot-pounds may be taken as a good average amount.

The metric horse-power, called by the French the *cheval-vapeur*, or *force de cheval*, is about $1\frac{1}{3}$ per cent less than the British, being $542\frac{1}{2}$ foot-pounds or 75 kilogrammetres per second, 4500 kilogrammetres per minute, or 270,000 per hour. These quantities are almost invariably employed to measure the power expended and work done by machines.

It is evident that power is also measured by the product of the resistance, or of the effort exerted into the velocity of the motion with which that resistance is overcome, or that force exerted. Since $s = vt$,

$$U = Rs = Rvt;$$

and when t becomes unity, the measure of the power, or of the equivalent work done in the unit of time, is

$$U' = Rv, \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad (5)$$

in which the terms are given in units of force and space as above.

The power of a prime mover is usually ascertained by experimentally determining the work done in a given time, the trial

usually extending over some hours, and often several days. It is measured in foot-pounds or kilogrammetres; the total work so measured is then divided by the time of operation and by the value of the horse-power for the assumed unit of time and the mean value of the power expended thus finally expressed in horse-powers.*

6. The Forces acting in machines are distinguished into *driving* and *resisting forces*. That component of the force, acting to produce motion in any part which lies in the line of motion only, is that which does the work; and this component is distinctively called the "Effort." Similarly, only that component of the resistance which lies in the line of motion is considered in measuring the work of resistance. In either case, if the angle formed between the directions of the motion of the piece and of the driving or the resisting force be called α, the effort is

$$P = R \cos \alpha. \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad (6)$$

The other component, acting at right angles to the path of the effort, is

$$Q = R \sin \alpha, \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad (7)$$

and has no useful effect, but produces waste of power by introducing lateral pressures and consequent friction.

7. Energy, which is defined as capacity for performing work, is either *actual* or *potential*.

Actual or *Kinetic Energy* is the energy of an actually moving body, and is measured by the work which it is capable of performing while being brought to rest, under the action of a retarding force; this work is equal to the product of its weight, W, into the height, $h = \frac{v^2}{2g}$, through which it must fall under the action of gravity to acquire that velocity, v, with which it is at the instant moving; i.e.,

$$E = U = Wh = W\frac{v^2}{2g}. \quad . \quad . \quad . \quad . \quad . \quad (8)$$

* Custom has not yet settled the proper form of the plural of this word; there is no reason why it should not follow the rule.

A change of velocity v_1 to v_2, causes a variation of actual energy, $E_1 - E_2$, and can be effected only by the expenditure of an equal amount of work—

$$E_1 - E_2 = U = W\frac{v_1^2 - v_2^2}{2g} = W(h_1 - h_2). \quad . \quad . \quad (9)$$

This form of energy appears in every moving part of every machine, and its variations often seriously affect the working of mechanism.

The total actual energy of any system is the algebraic sum of the energies, at the instant, of all its parts; i.e.,

$$E = \Sigma W\frac{v^2}{2g}; \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad (10)$$

and when this energy is all reckoned as acquired or expended at any one point, as at the driving-point, the several parts having velocities, each n times that of the driving-point, which latter velocity is then v, the total energy becomes

$$E = \Sigma W\frac{n^2v^2}{2g}. \quad . \quad . \quad . \quad . \quad . \quad . \quad (11)$$

Actual energy is usually reckoned relatively to the earth; but it must often be reckoned relatively to a given moving mass, in which case it measures the work which the moving body is capable of doing upon that mass, when brought by it to its own speed.

Potential Energy is the capacity for doing work possessed by a body in virtue of its position, of its condition, or of its intrinsic properties. Thus, a weight suspended at a given height possesses the potential energy, in consequence of its position, $E = Wh$, and may do work to that amount while descending through the height, h, under the action of gravity. A bent bow or coiled spring has potential energy, which becomes actual in the impulsion of the arrow or is expended in the work of the mechanism driven by the spring. A mass of gunpowder or other explosive has potential energy in virtue

of the unstable equilibrium of the chemical forces affecting its molecules. Food has potential energy in proportion to the amount of vital and muscular energy derivable by its consumption and utilization in the human or animal system. These potential energies are not measured by the observed actual energies derived from these substances in any case, but are the maximum quantities possibly obtainable by any perfect system of development and utilization. In practical application, more or less waste is always to be anticipated.

8. **The Law of Persistence of Energy** affirms that the total energy, actual and potential, of the universe, or of any isolated system of bodies, is of invariable amount, and that all energy is thus indestructible, although capable of transformation into various forms of physical and chemical energy.

Every instance of disappearance of actual energy involves the performance of work, and the production of potential or of some new form of actual energy in precisely equal amount. A stone thrown vertically upward loses kinetic energy as it rises in precisely the amount—resistance of the air being neglected—by which it gains potential energy. A falling mass striking the earth surrenders the actual energy acquired by loss of potential energy during its fall, and the equivalent of the quantity so surrendered is found in the work done upon the soil; it finally passes away as the equivalent energy of heat motion produced by friction and impact. The potential chemical energy of the explosive is the equivalent of the kinetic energy of the flying projectile, and the latter has its equivalent in the work done at the instant of striking and coming to rest, and in the heat produced by the final change of mass-motion into molecular or heat motion.

Energy in all its many forms is thus transferable in definite quantivalent proportions, and in all cases changes form when work is done. Work may therefore be defined as that operation which results in a change in the method of manifestation of energy, and Energy as that which is transferred or transformed, when work is done. The motion of a projectile is the transfer of energy from one place to another. It is generated at the point of departure, stored as actual or

kinetic energy, transferred to the point of destination, and there restored and applied to the production of work.

9. Acceleration and Retardation of masses in motion can only be produced by doing work upon them, or by causing them to do work, and thus, by the communication of energy to them or by its absorption from them, in precisely the amount which measures the variation of their actual energy as so produced. Every body which is increasing in velocity of motion thus receives and stores energy; every mass undergoing retardation must perform work, and thus must restore energy previously communicated to it. In every machine which works continuously, and in which parts are alternately accelerated and retarded, energy is stored at one period and restored at another, in precisely equal amounts.

Work done upon any machine may thus be expended partly in doing the useful work of the system, and partly in storing energy; and the same machine may do work at another instant partly by expending the energy received by it, and partly by expending stored energy previously accumulated.

10. Storage or Restoration of Energy thus always occurs when change of speed takes place. It is evident, since the storage or restoration of energy implies variation of speed, that the condition of uniform speed is that the work done upon the machine shall at each instant be precisely equal to that done by it upon other bodies. The work applied must be equal to that of resistance met at the driving-point. Thus,

$$\Sigma Pv = \Sigma Rv'; \int Pdv = \int Rdv'; \quad . \quad . \quad . \quad (12)$$

and the effort at each point in the machine will be equal to the resistance, and inversely as the velocity of the point to which it is applied; i.e.,

$$\frac{P}{R} = \frac{v'}{v}. \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad (13)$$

In the starting of every machine energy is stored during the whole period of acceleration up to maximum speed, and this energy is restored and expended while the machine is

coming to rest again. This latter quantity of energy is usually expended in overcoming friction.

11. The Useful and the Lost Work of a machine are, together, equal to the total amount of energy expended upon the machine, i.e., to the work done upon it by its "driver." The *Useful Work* is that which the machine is designed to perform; the *Lost Work* is that which is absorbed by the friction and other prejudicial resistances of the mechanism, and which thus waste energy which might otherwise be usefully applied. These two quantities, together, constitute the *Total Work* or the *Gross Work* of a machine, or of a train of mechanism. In every case some energy is wasted, and the work done by the machine is by that amount less than the work performed in driving it. In badly proportioned machines the lost work is often partly expended in the deformation and destruction of the members of the construction; in well designed and properly worked machinery loss occurs wholly through friction. In machines acting upon fluids this lost work is usually partly wasted in the production of fluid friction—i.e., of currents and eddies; thus producing new forms of actual energy in ways which are not advantageous: even this waste energy is finally converted, like the preceding form, by molecular friction into heat, and is dissipated in that form of molecular energy. Thus all wasted work is lost by conversion from the energy of mass-motion into molecular energy and ultimately disappears as heat.

12. The Efficiency of Mechanism is measured by the quantity obtained by dividing the amount of useful work performed by the gross work of the piece or of the system. It is always, therefore, a fraction, and is less than unity; which latter quantity constitutes a limit which may be approached more and more nearly as the wastes of energy and work are reduced, but can never be quite reached. If the mean useful resistance be R, and the space through which it is overcome be s', and if the mean effort driving the machine be P, and the space through which it acts be s, the total and the *net* or *useful work* will be, respectively, Ps, Rs'; the *lost work* will be $Ps - Rs'$ and the

$$\text{Efficiency} = \frac{Rs'}{Ps} < 1. \quad . \quad . \quad . \quad . \quad . \quad (14)$$

Counter-efficiency, C, is the reciprocal of the efficiency; i.e.,

$$C = \frac{Ps}{Rs'}. \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad (15)$$

The efficiency and the counter-efficiency of a machine, or of any train of mechanism, is the product of the efficiencies or of the counter-efficiencies of the several elements constituting the train transmitting energy from the point at which it is received to that at which the work is done, i.e., from the "driving" to the "working" point.

Friction is thus the principal cause, and usually the only cause, of loss of energy and waste of work in machinery. A given amount of energy being expended upon the driving-point in any machine, that amount will, in accordance with the principle of the persistence of energy, be transmitted from piece to piece, from element to element, of the machine or train of mechanism, without diminution, if no permanent distortion takes place and no friction occurs between the several elements of the train, or between those parts and the frame or adjacent objects. Temporary distortion, within the limit of perfect elasticity, causes no waste of energy; permanent distortion, however, causes a loss of energy equal to the total work performed in producing it. But permanent distortion is due to deficiency of strength and defective elasticity, and is never permitted in well-designed machinery properly operated; and hence the important principle:

The only cause of lost work in mechanism, which is to be anticipated in design and calculated upon in deducing the theory of special mechanism, is the friction necessarily consequent upon the relative motion of parts in contact and under pressure.

The study of the laws of friction, the construction of its theory, and the experimental investigation of the conditions which determine the loss of efficiency in machinery by friction, are thus obviously of supreme importance to the engineer who designs, the mechanic who constructs, and the operator or manufacturer who makes use of machinery.

In engineering, therefore, the principles of pure mechanism, of theoretical mechanics, and of pure theory in the science of energetics, or of thermodynamics, are to be studied as introductory to a science of application in which all actions and all calculations are to be considered with reference to the modifications produced by the wastes of energy and the alteration of the magnitudes and other properties of forces consequent upon the occurrence of friction. This is to the engineer a vitally important branch of applied science, and it is coextensive with the applications of mechanical science.

13. **The Magnitude of the Lost Work** in machinery and mill-work is variable, but is always very large. It may probably be fairly estimated that one half the power expended in the average case, whether in mill or workshop, is wasted in lost work, being consumed in overcoming the friction of lubricated surfaces. That this is true, is evident from the fact that the power demanded to drive the machinery of such establishments has been found by Cornut and others to be variable to the extent of 15 or 20 per cent by simple change of temperature indoors from summer to winter, and a reduction of 50 per cent in the work lost by friction has often been secured by change of lubricant. Mr. Fairbairn has found a change to the extent of 10 to 15 horse-power in a cotton-mill from the former cause.

The friction of shafting in mills varies, with size and loading, from 0.33 to 1.5 horse-power per 100 feet (31 m.) length, averaging for the "main line," with good lubrication, about 1 horse-power. The loss of power in mills ranges, with different machines, from 5 to 90 per cent, averaging for cotton and flax mills about 60 per cent, with good management, and in woollen mills about 40 per cent, the efficiencies being therefore about 40 and 60 per cent for the two cases. The friction of heavy iron-working tools may be taken at about $f = 0.15$, the efficiency at 0.85. The loss in the steam-engine is usually nearly constant at all powers, and ranges from 4 pounds per square inch (0.27 atmosphere) on small engines of 25 to 50 horse-power, down to 1 pound (0.07 atmosphere) in very large marine-engines: this gives efficiencies ranging from 0.84 to 95

or 97 per cent. In a "high-speed" engine intended to drive electric lights the author found the efficiency to be

$$\text{Efficiency} = 1 - \frac{0.06}{U},$$

in which U is the work done, calling work "at full stroke" unity. Rules for calculating the magnitude of this loss will be given in later chapters.

CHAPTER II.

NATURE AND THEORY OF FRICTION.

14. **Friction** is that familiar resisting force which always acts to prevent or to retard the relative motion of one particle or body in forced contact with another. It is of three kinds: sliding and rolling friction, acting between solids; and fluid friction, which acts when the particles of liquids or of gases move in contact with each other or with other bodies. These three kinds of friction are different in character, and are governed by quite different laws; these laws also are in many cases quite different from those usually given in earlier works on this subject.

Friction acts at the surfaces of contact of the two particles or masses between which it is exhibited, and in the direction of their common tangent, resisting relative motion, in whichever direction it may be attempted to produce it. Friction is thus always a resisting force, and never of itself produces or accelerates motion. It may act usefully in increasing the stability of structures, or injuriously by resisting the motion of mechanisms, and by producing waste of power and work; it may also be utilized in the absorption of surplus energy, or in the transmission of motion from one to another of movable parts in contact.

In any simple machine or in any train of mechanism, if either be absolutely rigid or absolutely elastic,—i.e., not subject to deformation,—the only losses of energy are those produced by friction. This important principle has the important corollary, that the "efficiency" of a machine is known when all its frictions are determinable.

Friction of motion, whatever the kind considered and whatever its cause, always results in the conversion of an

amount of energy, measured by the work of friction, into heat. In accordance with the law of the "persistence of energy," and with the "first law of thermodynamics," this production of heat occurs, in every case, in the proportion of one British thermal unit for each 772 foot-pounds of work absorbed by friction, or of one metric heat-unit for each 423.55 kilogrammetres of energy so lost. The amount of heat produced may therefore be calculated by dividing the total work of friction, for any given case, by this "mechanical equivalent of heat." Thus one horse-power expended in friction results in the conversion of work or energy into

$$\frac{33{,}000}{772} = 43 \text{ "B. T. U.,"}$$

(British thermal units,) per minute; 10 *chevaux de vapeur* similarly expended in overcoming friction, produce

$$\frac{750}{423.55} = 1.8 \textit{ Calories},$$

(metric thermal units,) per second, or 108 per minute nearly.

15. **Moving and Resisting Forces** are met with in all mechanical processes. The former are those which are active, and produce or tend to produce change of motion in bodies; the latter are those which are purely passive, and only resist the action of forces of the first class. Gravity, heat-energy, and all other energies, including that of muscular force, illustrate the first, and friction is of the second, class. Moving forces may either produce or destroy motion; but resisting forces can only resist and reduce motion. Forces of the first class are definite, and may be entirely independent of the forces by which they are opposed or aided; those of the second class are indefinite in direction, and, within limits, in magnitude, and are variable with the magnitude, direction, and point of application of the moving forces which they oppose. Moving forces are evidently in their nature determinate; resisting forces are as obviously in their nature indeterminate.

Friction is evidently of this latter class; and the *Force of Friction* has a variable magnitude, from 0 to its maximum, fW, with variation of the active force which it may resist.

16. The Friction of Solids is caused by the roughness and unevenness of the surfaces of contact. In the case of *Sliding Friction* the asperities of the one surface interlock with those of the other, and motion can only take place by the riding of the one set over the other, by the tearing off of the projecting parts, or by rubbing them down: in either case the process gives rise to a resistance which is the greater as the roughness is greater, and the less as the surfaces are smoother; an absolutely smooth surface would be frictionless. *Rolling Friction* is observed where any surface of revolution, or other smoothly curved surface, is rolled upon another surface, plane or curved. Its cause is identical with that of sliding friction, that irregularity of form and of surface which will not permit motion to occur without irregular variation of the distance between the centre of gravity of the rolling body and the line of motion in the common tangent of the two bodies, at the point or line of contact. Where the surfaces are hard, smooth, and symmetrically formed, this friction is small; where they are soft, rough, or irregular, this form of friction is observed in greater degree, Absolutely smooth, hard spheres or cylinders, rolling on absolutely hard, smooth surfaces, meet with no frictional resistance; bodies having rough surfaces, those made of compressible material, and those of irregular surface and form, exhibit greater friction as these defects are exaggerated. Both forms of resistance evidently depend upon the character of the material as well as upon the form of the surfaces of contact.

The resistance of knife-edges, as in balances, is a form of rolling friction.

17. The Laws of Sliding Friction, with solid, unlubricated surfaces, are, up the point of abrasion, as follows:

(1) The direction of frictional resisting forces is in the common tangent plane of the two surfaces, and directly opposed to their relative motion.

(2) The point or surface of application of this resistance is the point or the surface on which contact occurs.

(3) The greatest magnitude of this resisting force is dependent on the character of the surfaces, and is directly proportional to the force with which the two surfaces are pressed together.

(4) The maximum frictional resistance is independent of the area of contact, the velocity of rubbing, or any other conditions than intensity of pressure and condition of the surfaces.

(5) The friction of rest or quiescence, "statical friction," is greater than that of motion, or "kinetic friction."

These "laws" are not absolutely exact, as here stated, so far as they affect the magnitude of friction-resistance.

It is found that the resistance to sliding of "skidding" wheels on railways is less as speed is greater; but it is not known to what extent this is due to the separation by jarring of wheel and truck. It is also found that some evidence exists indicating the continuous nature of the friction of rest and motion.

When the pressure exceeds a certain amount, fixed for each pair of surfaces, abrasion of the softer surface or other change of form takes place; the resistance becomes greater, and is no longer wholly frictional. When the pressure falls below a certain other and lower limit the resistance may be principally due to adhesion, an entirely different force, which may enter into the total resistance at all pressures, but which does not always appreciably modify the law at higher pressures. This limitation is seldom observable with solid, unlubricated surfaces, but may often be observed with lubricated surfaces, the friction of which, as will be presently seen, follows different laws. The upper limit should never be approached in machinery, but is often reached in framed structures.

18. The Coefficient of Friction is that quantity which, being multiplied by the total pressure acting normally to the surfaces in contact, will give the measure of the maximum frictional resistance to motion. It follows from the third law

above stated (Art. 17), that the greatest force with which relative motion is resisted by friction is obtained by thus multiplying this total pressure by a constant coefficient to be determined experimentally for every pair of surfaces of definite character. Thus, if N represent the normal force binding the one surface to the other, if F be the maximum resistance due to friction, and if f be the coefficient of friction,

$$F = fN; \qquad f = \frac{F}{N}.$$

The value of f being determined by experiment, it is constant, within the limit already stated, for all pressures occurring between the given surfaces. As will be seen later, its value is variable for lubricated surfaces with variations of velocity, of intensity of pressure, of temperature, and probably with other conditions.

19. The Methods of determining Coefficients of Friction are usually very simple. Where a heavy body, W (Fig. 1),

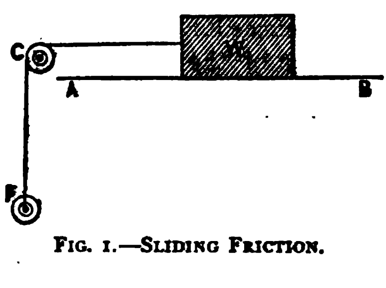

FIG. 1.—SLIDING FRICTION.

slides upon a plane, AB, the magnitude of the force, F, required to cause motion, or to continue motion once started, can be determined by carrying a cord over a pulley, C, and, one end being attached to the mass to be moved, and the other being loaded with such a weight, F, as is needed to cause motion or to keep up a given velocity of sliding, the value of the coefficient, f, becomes known, and we have

$$f = \frac{F}{W}.$$

The force F may often be most conveniently measured by a spring balance attached to a cord pulling in the line of motion of W.

An equally easy method of ascertaining the value of f is illustrated in Fig. 2. An inclined plane AB, of variable angle

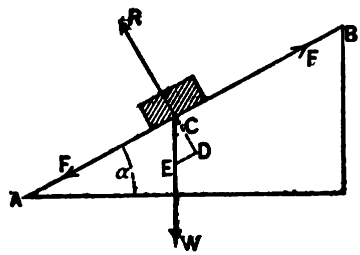

FIG. 2.—SLIDING FRICTION.

of inclination, α, is constructed of one of the materials between which the friction is to be determined; while a body of any convenient size, and of the same or other material, as may be desired, is placed upon the inclined surface. To determine the coefficient of friction for rest, the plane is raised to such an angle, α, that the body will just start down the plane without the application of an external impelling force. At this instant the friction is due to the pressure produced by that component, CD, of the weight which produces the normal pressure, and which is equal to the reaction, R, of the surface against the sliding body; it is measured by

$$fR = fW \cos \alpha,$$

as well as by that component of the total weight, W, acting along the plane to cause sliding. Hence

$$fR = fW \cos \alpha = W \sin \alpha;$$
$$f = \frac{\sin \alpha}{\cos \alpha} = \tan \alpha:$$

and the value of the coefficient of friction is equal to the

tangent of the inclination of the plane. Otherwise, resolving parallel and perpendicular to the plane, we have

$$fR - W \sin \alpha = 0,$$
$$R - W \cos \alpha = 0;$$

then, eliminating R and W, we have

$$f \cos \alpha - \sin \alpha = 0,$$

or, as before,

$$f = \tan \alpha.$$

The angle α is often called the *angle of friction*, or the *limiting angle of resistance*, and is usually designated by the letter φ.

Various other methods are used, some of which will be described in later chapters, in which accounts of experimental work will be given.

The coefficient of friction, f, is by many writers denoted by the letter μ.

20. Angle of Friction; Cone of Resistance.—The total action of any surface upon a body moving in contact with it is the resultant of two components, one of which is the reaction, R, in a line normal to the surface, and the other of which is the resisting force of friction, F, equal and opposite to the effort tending to produce motion along the surface; these two forces are therefore at right angles to each other, and their resultant is

$$\varphi = \sqrt{R^2 + F^2},$$

and its direction may be such as to make any angle with the tangent and the surface greater than 0, or less than $\varphi = \tan \quad f$. Exceeding the latter limit, accelerated motion takes place.

The movable body will evidently remain at rest, whatever the direction of this resultant force, provided its direction does not fall outside a cone of which the apex is at the point of application of the resultant force, and of which the semi-angle is $= \tan^{-1} f$. This Angle of Friction, φ, thus deter-

mines the *Cone of Friction*, as it is usually called; which cone is generated by causing the line defining the angle of friction to revolve about the normal: this cone thus embraces the direction of all possible forces which do not produce motion. When the cone of friction is referred to without qualification, the friction implied is usually statical friction—the friction of rest.

It follows from what has preceded, that the stability of a system composed of a pair of bodies in contact is determined by the angle of friction and the location and the form of the cone of friction, and that the greatest angle of obliquity of the resultant pressure in a stable system is the angle of which the tangent is equal to the coefficient of friction; this is the *angle of repose*, φ. For cases of equilibrium, the force of friction is $fN = N \tan \varphi = W \sin \varphi$, where W and N are respectively the applied force and its normal component.

21. The Friction of Rest, or Statical Friction, although in the case of the sliding of solids precisely of the same nature as the friction of motion or dynamical friction, is often of very different magnitude and sometimes follows different laws: the former is always greater than the latter, and where the pressure is of great intensity is frequently enormously greater than when the relative velocity of the rubbing surfaces is considerable. The friction of rest is also often increased, especially where one or both of the surfaces is of soft material, by time of contact. This apparently comes of the fact that the two surfaces when left under pressure, imbed themselves, the one in the other, more and more thoroughly as time passes, until in some instances adhesion occurs, and the frictional resistance to starting them apart is reënforced by molecular forces. With hard bodies and with light pressures these differences are less observable, and are often unimportant.

The magnitude of the coefficient of friction for rest is very variable, but usually increases with increasing pressures; its value for special cases will be given in a later chapter.

22. The Friction of Motion, or Kinetic Friction, only differs from statical friction in its magnitude. It is always less between any given pair of surfaces and under any given

pressure than statical friction, with the conditions, other than the difference as to motion, the same. The value of its coefficient is less as velocity increases from zero, passes usually if not in all cases a minimum, and then increases again; it becomes less as pressure increases, up to a limit also, passing which it again increases until abrasion occurs.

With lubricated surfaces these differences become more observable than with dry surfaces, and the methods of variation, as will be seen later, often differ greatly.

The direction of either form of the Force of Friction is always, as has been seen, directly opposed to the direction of motion, or of the resultant forces attempting to produce motion; and its magnitude is always just sufficient to equilibrate the resultant moving force, up to a maximum which is reached when that force becomes equal to the maximum resistance, fN.

23. **The Differences between the two Frictions** are evidently of such magnitude as to be of very great importance in construction. It is found that a jar, often a very slight one, will convert the friction of rest into the friction of motion, and, motion once commenced, it continues with acceleration of velocity until the total resistance equilibrates the resultant impelling effort. In machinery, therefore, it is often difficult to set the train in motion, but comparatively easy to sustain a velocity once acquired. A train on a railway may be started, the friction of rest being overcome by jar in one car after another, when loosely "coupled;" while the same locomotive may be quite incapable of starting a train of the same size and kind, closely and rigidly coupled. Once in motion, the two trains are moved with equal ease. The greater the intensity of the pressure, the greater the difference in resistance, and the more difficult it is to convert the one form into the other. It is probable that the law of variation, so far as it relates to speeds of rubbing, is continuous, the coefficient insensibly changing as speed decreases to the value of rest, as the velocity passes through insensibly small values to 0.

As the slightest jar will usually convert the friction of rest into friction of motion, no machinery subject to jar need be stud-

ied with reference to the modification of its efficiency by the former kind of friction. In any system subject to jar, also, the parts normally at rest will gradually assume the positions which a similar system absolutely at rest would take if perfectly frictionless. This principle is very often of practical importance. This does not reduce the lost work in a train of moving machinery to zero, however, as work is expended in producing the jarring.

Motion in one direction also reduces or may even eliminate the effect of friction in another direction. Thus, in the hydraulic testing-machine of Mr. C. E. Emery the rotation of the "ram" of the hydraulic press eliminates the effect of friction in its longitudinal movement, and permits as exact measurement of the resistance of the test-piece as if the plunger or ram were frictionless.

24. **The Principle of Equilibrium,** as it is termed, for cases in which it is attempted to move bodies against the force of friction is the following:

Determine the reaction of the supporting surface under the actual or assumed conditions, by finding the resultant of all other forces acting upon the supported body; then if the direction of this resultant falls within the cone of friction equilibrium will exist, the body will remain at rest, and the resistance of the surface is equal and directly opposed to this resultant.

The single condition of equilibrium and rest is, therefore, that the applied forces should have a resultant lying within the cone of friction. The magnitude of the force of friction is determined in such cases of equilibrium by resolution of the resultant obtained, as above, into components parallel and perpendicular to the surface at its point of application, and measuring the parallel component, which is the force of friction.

25. **A Solid resting on any actual Surface,** even if both are apparently ever so hard and smooth, will nevertheless always be connected with it by projecting and interlocking particles, which may be microscopic or less than microscopic in size, but which may offer appreciable resistance to motion. The two bodies being left in contact, their surfaces gradually

come into more and more intimate contact, bringing new sets of particles into connection, and imbedding the set first in contact more thoroughly, until a permanent condition is reached. The coefficient of friction and the force of friction then attain maximum values, and offer greatest resistance to motion. At any given instant, if f represent the coefficient of friction, N the normal reaction of the surface, and α the angle made by the acting force, W, with the surface itself, the force of friction will be fN, and the body will remain at rest so long as the component of the applied resultant force parallel with the surface is less than this quantity, $fN = W \sin \alpha$.

In illustration of the theory of friction on planes, let it be required to determine the inclination, α, of a prismatic body, as a beam, AB (Fig. 3), resting at one end upon a horizontal surface, AC, and at the other end against a vertical surface, BC, when just in equilibrium and about to slide down.

Let its length $AB = l$, $l' =$ the distance of its centre of gravity from its foot, and let f and f' be the coefficients of friction, for rest, on the horizontal and vertical surfaces respectively, and R and R' the reactions of those surfaces at the points of contact; let W be the weight of the beam.

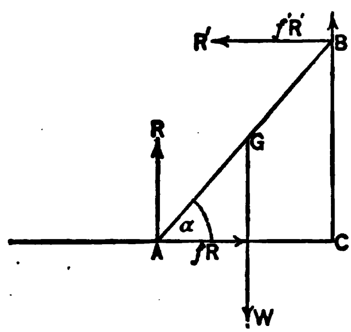

Fig. 3.—Friction of Solids.

Resolving, we have

$$R' - fR = 0,$$

$$R + f'R' - W = 0,$$

$$W = R(1 + ff'),$$

and $R' = fR$.

Taking moments about A,

$$W.l'.\cos\alpha - R'.l.\sin\alpha - f'R'.l.\cos\alpha = 0,$$

$$\tan\alpha = \frac{W.l' - f'R'l}{R'l},$$

$$\tan \quad = \frac{l'.(1 + ff') - lff'}{fl}$$

If the centre of gravity of the beam is at the middle, $l = 2l'$, and

$$\tan \alpha = \frac{1 - ff'}{2f}.$$

26. A Solid resting on an Inclined Plane, and acted upon by its own weight and by external forces, is the simplest and best illustration of the general case.

The following proposition will illustrate the mathematical application of the principles of the theory of friction to this case:

(1) To determine the limiting ratios of P to W, friction acting up or down the plane, AB (Fig. 4), when P represents the effort exerted on the sliding body, W is its weight, and R is the reaction of the plane, which makes an angle, α, with the horizontal.

Let the force, P, make an angle, β, with the surface of the plane, AB, the body moving up the plane.

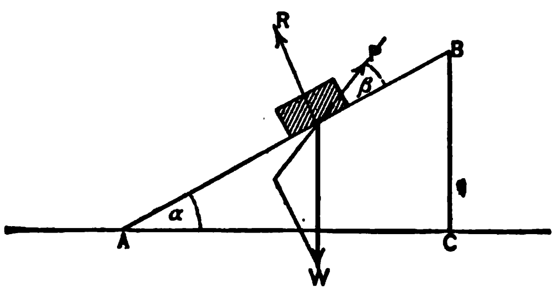

FIG. 4.—THE INCLINED PLANE.

Since there exists an equilibrium of forces, we shall have, for the maximum value of P,

$$P \cos \beta - fR - W \sin \alpha = 0,$$
$$P \sin \beta + R - W \cos \alpha = 0,$$

whence $$P = \frac{W(\sin \alpha + f \cos \alpha)}{\cos \beta + f \sin \beta}. \quad \quad (1)$$

For a minimum value, we get, when the body slides down,

$$P\cos\beta + fR - W\sin\alpha = 0,$$
$$P\sin\beta + R - W\cos\alpha = 0,$$

and
$$P = \frac{W(\sin\alpha - f\cos\alpha)}{\cos\beta - f\sin\beta} \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad (2)$$

Motion cannot occur if the value of P falls within the two limits above deduced, if f be taken as the coefficient of friction for rest. If taken for motion, the velocity will be constant in the two cases taken, and accelerated for intermediate values of P, the body moving down the plane; and retarded motion occurs if the body moves up the plane.

(2) Making $P = 0$, we have

$$\sin\alpha - f\cos\alpha = 0,$$
$$f = \tan\alpha = \tan\varphi, \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad (3)$$

as before, and the tangent of the angle of inclination of the plane measures the coefficient of friction for rest, if the body is in equilibrium without motion, or the coefficient for motion if the body slides with uniform velocity.

(3) If the effort act in the surface of the plane, $\beta = 0$, and

$$P = W(\sin\alpha \pm f\cos\alpha), \quad . \quad . \quad . \quad . \quad . \quad (4)$$

the positive sign being taken for a pull up the plane, and the negative for an effort acting down the plane. The difference is

$$\Delta P = 2fW\cos\alpha. \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad (5)$$

(4) Making $f = 0$, we have

$$\frac{P}{W} = \sin\alpha = \frac{BC}{AB}, \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad (6)$$

and the effort is to the weight of the body as the height of the plane is to its length.

(5) When the effort is parallel with the base, $\beta = -\alpha$, and

$$P = \frac{W(\sin\alpha \pm f\cos\alpha)}{\cos\alpha \mp f\sin\alpha}; \quad . \quad . \quad . \quad . \quad . \quad (7)$$

and when $f = 0$,

$$\frac{P}{W} = \tan\alpha = \frac{BC}{AC}, \quad . \quad . \quad . \quad . \quad . \quad . \quad (8)$$

the effort being to the weight as the height of the plane is to the length of its base.

(6) In the case of a prismatic body, as a beam (Fig. 5), resting on the curved surface of a cylinder, the weight that may be suspended at the end without causing it to slide may be determined readily by the application of the principles above given.

Let G be the centre of gravity of the beam AB (Fig.), whose length is $2l$, and $BG = l$, the beam being uniform, $W =$ its weight, and W' the weight suspended from the end B. Before the weight W' was suspended from the beam the point G evidently was at C. Let C' be the point of contact with the cylinder, the beam being on the point of sliding off, α the angle it makes with the horizon, and $r =$ the radius of the cylinder.

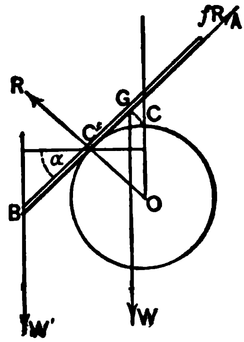

FIG. 5.—SLIDING FRICTION.

Resolving parallel and perpendicular to the beam, we have

$$fR - W\sin\alpha - W'\sin\alpha = 0,$$
$$R - W\cos\alpha - W'\cos\alpha = 0;$$

$$f = \tan\alpha.$$

Taking the moments about C', we have

$$W'.BC'\cos\alpha - W.C'g.\cos\alpha = 0,$$

or

$$W'.(BG - A'g) - W.C'g = 0.$$

But $C'g = \text{arc } C'C = \text{radius} \times \text{angle } C'OC' = r.a.$

$$\therefore\ W'.(l - ra) - W.ra = 0,$$

and $$W' = \frac{W.ra}{l - ra} = \frac{W.r \tan^{-1} f}{l - r \tan^{-1} f},$$ the weight required.

(7) Let the cylinder diminish in size until its diameter may be neglected; and let the end of the beam, AB (Fig. 6), rest against a vertical wall at β. Then the position of equilibrum is found thus:

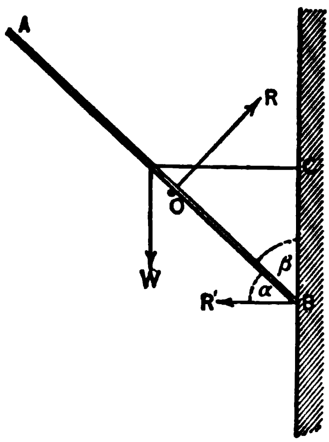

Fig. 6.—Sliding Friction.

The forces now acting are, the weight of the beam, W; the pressure on the support, equal to the reaction, R; and the pressure on the wall, equal to the reaction R'. W acts vertically downward, R perpendicularly to the beam, and R' perpendicularly to the face of the wall. The half length, l, of the beam, and the distance, $CO = d$, from the support to the wall are known, and the position of equilibrium becomes known when the angle, α, between the beam and the perpendicular to the wall, or its complement, β, the angle with the face of the wall, is known.

We have, without friction,

$$d = CO = BO \sin \beta; \qquad BO = \frac{CO}{\sin \beta}; \quad . \quad . \quad . \quad (1)$$

and, resolving horizontally and vertically,

$$R' - R \cos \beta = 0; \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad (2)$$

$$W - R \sin \beta = 0. \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad (3)$$

Also, taking moments about B,

$$RBO - Wl \sin \beta = 0; \quad . \quad . \quad . \quad . \quad . \quad (4)$$

$$Rl - Wl \sin^2 \beta = 0. \quad . \quad . \quad . \quad . \quad . \quad (5)$$

Then, combining equations,

$$\sin^2\beta = \frac{d}{l}; \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \qquad (6)$$

$$R = \frac{W}{\sin\beta}; \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \qquad (7)$$

$$R' = R\cos\beta = W\operatorname{cotan}\beta, \quad . \quad . \quad . \quad . \quad . \qquad (8)$$

which gives the values of all three unknown quantities, when the wall and support are smooth.

Where friction enters, we have motion opposed by it, although no tendency to motion exists for the position just determined. If the rod be moved from this position, the end B being gradually carried downward, along the wall, the force of friction gradually increases, but no motion can occur from any of the successive positions until a certain limit is reached, when the tendency to slide is sufficient to overcome the frictional resistance and a new position of equilibrium is thus found. In this position a force of friction, fR', acts upward at B, and a force, fR, resists sliding at O, acting in the direction, BO.

The equations of equilibrium now become

$$R' - fR\sin\beta - R\cos\beta = 0; \quad . \quad . \quad . \quad . \qquad (9)$$
$$W - fR' - R\sin\beta = 0; \quad . \quad . \quad . \quad . \qquad (10)$$
$$Rd - Wl\sin^3\beta = 0;$$

and finally, eliminating R and R',

$$1 - \frac{l}{d}\sin^3\beta = f\frac{l}{d}\sin^2\beta\,(\cos\beta - f\sin\beta); \quad . \quad . \qquad (11)$$

which will determine β.*

Finally, carrying the end of the beam upward, a similar

* See Thomson and Tait; Nat. Phil., vol. i., § 572.

process will give the position of equilibrium when the frictions act in the opposite direction, and the equation becomes

$$\frac{l}{d}\sin^2\beta - 1 = f\frac{l}{d}\sin^2\beta\,(\cos\beta + f\sin\beta). \quad . \quad (12)$$

(8) Suppose a rectangular block to lie upon a horizontal plane; to determine whether it will slide or turn over, we have, known, the reaction of the plane,

$$R = W; \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad (1)$$

the resistance of friction, equal to the effort

$$P = fR = fW; \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad (2)$$

and the moments of P and of W equal for the position of equilibrium, and if the half thickness of the block be t and the height of the point of application of the effort be h,

$$Wt = Ph; \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad (3)$$

$$P = \frac{t}{h}W. \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad (4)$$

Hence, if the maximum pull, P, is less than fW, i.e., if

$$f > \frac{t}{h}, \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad (5)$$

the mass may be overturned.

It is evident that the body will not turn if the resultant of the weight of the mass, and the maximum effort to move it, i.e., the maximum effort permitted by friction, pierces the supporting plane within the base of the prism.

(9) A heavy body, *ABCD*, is secured to two rings, *FG*, which may slide on a vertical post, *HK*, and is so formed or so loaded, that its centre of gravity falls at a known point, *E*.

The reaction of the point *A* must evidently take the direction *AE*; that of *D*, the direction *DE*; and the only other force, if no friction exists, is the weight of the mass, *W*, acting vertically through *E*. This system of forces is extended by the introduction of friction to include a vertical force resisting sliding, acting upward at the rings; and the impelling effort will always be the difference between the newly introduced force and the weight. The magnitude of the force of friction is found by multiplying the horizontal components, *R*, *R'*, of the forces in *FE*, *GE*, by the coefficient of friction, *f*; and it is evident that, by making the distances between the rings small enough, and the distance out to the centre of gravity of the mass great enough, we may always make

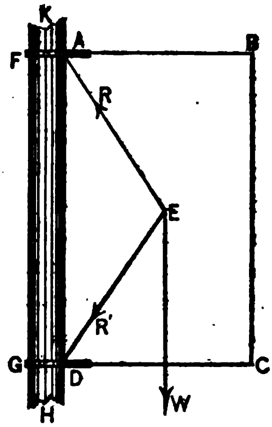

FIG. 7.—SLIDING FRICTION.

$$f(R+R') > W,$$

and thus secure conditions which prevent the descent of the body along the supporting post.

27. Solids moving on rough Surfaces are subject to precisely the same conditions at each instant that obtain where the body is simply at rest, and resisting an effort tending to produce motion. Kinetic friction differs, however, from statical friction, as has been stated, in the fact that the force of friction is always the maximum obtainable with the existing value of the coefficient, while in the case of statical friction that is the maximum limit simply; they also differ in the fact that the coefficient for motion often varies from instant to instant, and the direction of the force must also constantly change if the direction of motion varies, the two directions being always directly opposed.

When motion occurs against the force of friction, the effort required to overcome it is lessened the instant that motion begins, and may afterward increase or diminish according to circumstances, some of which will be described later. In all cases, since the resistance is overcome by a constantly exerted effort acting through measurable spaces, work is done in measurable amount, and an equivalent amount of mechanical energy is transformed in all cases into heat-energy. This occurs, as already stated, in the proportion of one British thermal unit to each 772 foot-pounds of work, or of one metric thermal unit for each 423.55 kilogrammetres. The work of friction is therefore a quantity of importance to the engineer for two reasons: if excessive in amount, it absorbs and wastes a seriously large amount of otherwise available and useful energy; it also converts all this energy into heat, which heat may give rise to inconvenience, injury of parts, or even destruction of the machine. Provisions must always be made, therefore, to reduce and to carry away this heat, if of considerable amount, in such a manner as to do no damage. This is often a problem of very serious importance, and not infrequently is very difficult of solution. The work of friction is always measured by the quantity, fNs, in which f is the coefficient of friction, N is the normal pressure on the supporting surface, and s is the distance traversed on that surface.

The friction of motion, or kinetic friction, is less variable, where the same two surfaces are used, than the static form of friction; but it is always different in amount under the same pressures. These differences are exaggerated where lubrication is resorted to. The coefficient of friction for motion may often remain nearly constant for a vastly wider range of pressure than that for rest, and the work done against friction is correspondingly uniform.

The condition of equilibrium, the body being in a state bordering upon motion, is that the direction of the resultant pressure shall lie in the surface of the *static* cone of friction. The condition that the body shall start from its state of rest is that this pressure shall be directed in a line exterior to that cone. The condition of uniform motion is that the direction

of that pressure shall subsequently lie in the surface of the cone of friction defined by the coefficient of *kinetic* friction. The conditions of accelerated and of retarded motion are that the direction of pressure shall fall outside of or within the latter surface, as the case may be. A body starting into free motion, under the action of an effort just sufficient to overcome the friction of quiescence, will move with accelerated velocity, the acceleration being proportional to the difference between the friction of rest and that of motion. Conversely, a body being in a state of equilibrium under the action of any set of forces, if the body be at rest, the line of direction of the resultant of all forces, other than the reaction of the supporting surface, must be coincident with an element of the static cone of friction; if the body be in kinetic equilibrium, moving with uniform velocity, the resultant effort must be coincident with an element of the cone of kinetic friction.

Where a heavy piece (Fig. 8) slides upon a smooth plane, the simplest method of treatment is to combine the weight of the piece with the resistance, R, which is also known in magnitude, direction, and point of application, and thus to determine a "given force," R', as defined by Rankine. The line of action of the effort, P, causing equilibrium or motion is known. Let the angle, α, be made by the "given force" with the surface of the plane; let β be the angle made by the effort, or the "driving force," P, with the same plane, and call the coefficient of friction f.

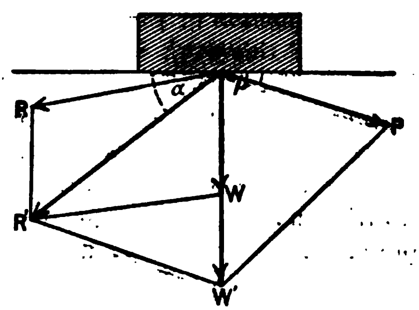

FIG. 8.—SLIDING FRICTION.

Then the total pressure on the plane is

$$R' \sin \alpha + P \sin \beta = W'. \quad . \quad . \quad . \quad . \quad (1)$$

The friction is

$$fW' = f(R' \sin \alpha + P \sin \beta). \quad . \quad . \quad . \quad (2)$$

The resistance to sliding is

$$R' \cos\alpha + fW' = R' (\cos \alpha + f \sin \alpha) + Pf \sin \beta ; \quad (3)$$

$$= P \cos \beta. \quad . \quad . \quad . \quad . \quad (4)$$

The work done against friction is

$$fW's = fs.(R' \sin \alpha + P \sin \beta), \quad . \quad . \quad . \quad . \quad (5)$$

where

$$P = \frac{R' (\cos \alpha + f \sin \alpha)}{\cos \beta - f \sin \beta}. \quad . \quad . \quad . \quad . \quad (6)$$

Examples illustrating Kinetic Friction are constantly met with in machinery. Such cases will be taken in some detail in a later chapter, while this phenomenon as exhibited in the elementary parts may be treated here.

In all cases, as previously stated, the action of friction in a machine results in the increase of the effort required to drive it, and hence in the compulsory enlargement and strengthening of parts and of the frame of the machine; it also causes a waste of energy measured by the total work of friction, and a reduction of the efficiency of the machine by the conversion of this work into heat-energy; and hence it compels the application of greater power and the use of a larger and stronger machine than would be otherwise needed to do the given work. The following cases illustrate the more important principles involved in the working of mechanism subject to friction:

(1) Let any body be moved along a surface on which it presses with its full weight, and for which the coefficient of friction is known, the surface having a varying inclination. Determine the work of friction.

For a surface of varying inclination, α, and the effort acting in the surface, from the principle of equality of energy exerted and work performed, if ds is the space traversed and U the work,

$$dU = Pds = W \sin \alpha \, ds + Wf \cos \alpha \, ds. \quad . \quad . \quad (1)$$

But for any small movement, if dh is the height and dl the horizontal distance traversed,

$$dh = ds \,.\, \sin \alpha; \qquad dl = ds \,.\, \cos \alpha;$$

and

$$Pds = W \,.\, dh + W \,.\, fdl;$$

whence, integrating

$$U = Ps = W(h + fl), \quad . \quad . \quad . \quad . \quad . \quad . \quad (2)$$

and the total work is the sum of the work done in raising the body through the height $h = BC$ (Fig. 4), and in sliding the mass, against friction, through the space, $l = AC$; and it is in no way influenced by the form of the path from A to B.

(2) The best value of the angle β is found by making the value of P a minimum, i.e., making $\cos \beta + f \sin \beta$, in equation (1), § 26, a maximum; and we have

$$f \cos \beta - \sin \beta = 0;$$

$$\beta = \tan^{-1} f; \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad (3)$$

whence it follows that β should be equal to the angle of friction and positive, the direction of P rising above that of the surface of the plane, making an angle at every instant with the tangent plane to the surface, at the point of contact, equal to the kinetic angle of friction.

(3) A body moving in any known path and with any given initial energy, $\frac{1}{2}MV^2 = Wh = U$, being retarded by friction, it is easy to determine the space through which it will move before expending its energy and coming to rest.

For from the law of equivalence of energy expended and work performed,

$$\tfrac{1}{2}MV^2 = Wh = fNs = U; \quad . \quad . \quad . \quad . \quad . \quad (4)$$

and hence

$$s = \frac{MV^2}{2fN} = \frac{Wh}{fN} = \frac{U}{fN}, \quad . \quad . \quad . \quad . \quad . \quad (5)$$

and the space may be found by dividing the initial energy by the mean value of the product of the coefficient of friction, f, into the normal pressure, N, at the point of contact between the two bodies.

This is true for all possible cases. Thus a heavy body thrown along the surface of smooth ice moves farther than on a surface of wood, the initial velocity being the same, because the force of friction is less and the distance traversed in doing the same work is correspondingly greater. A fly-wheel, revolving on its shaft-journals, if unacted upon by external forces, turns until the work of friction in the journals and in the air in contact with it is sufficient to abstract all its initial energy of rotation; and, neglecting the effect of the resistance of the air, the product of the pressure on the journals into the mean coefficient of friction, being multiplied by the velocity of rubbing of the journal-surface and by the time, the product is the work so done, and is equal to the total initial energy of the wheel.

(4) *A Taper Key*, such as is used in machinery, illustrates a common application of the principles controlling friction of moving bodies on inclined planes. If the half-angle of the "taper" of the key is α, the effort required to start it is proportional to the coefficient for rest; but as the impact of each blow starts the key, the effort causing motion is determined by the value of the coefficient for rest, and this effort is, when P is the pressure on the key,

$$F = P \tan \varphi + P \tan (\alpha + \varphi);$$

the work done is, when W is the striking weight and v its velocity,

$$W \frac{v^2}{2g} = Fs = Ps [\tan (\alpha + \varphi) + \tan \varphi)];$$

while for backing out the key,

$$F = P \tan [\tan (\varphi - \alpha) + \tan \varphi];$$

$$W \frac{v^2}{2g} = Ps [\tan (\varphi - \alpha) + \tan \varphi];$$

s being the space through which the resistance P may be taken as acting. Maximum rigidity and inelasticity of parts would make s approximate 0.

When $\tan(\varphi - \alpha) + \tan\varphi = 0$, $\varphi - \alpha = -\varphi$, and $\alpha = 2\varphi$; and with this value of α no force is needed to "slack" the key. For well-finished keys, $f = 0.10$, when the surfaces are not lubricated more than is commonly the effect of handling, and α may be taken above 10°, i.e., a taper of about one to six; more usual values are 1 : 50 to 1 : 100 for keys fitted to gibs, and half these values for cotters, or keys without gibs.

28. The Distribution of Pressure on surfaces subject to wear by the friction of motion depends greatly upon their form and on the character of that motion. Plane surfaces, if rigid and subject to the wear of straight-sliding parts, of which they form the bearing surfaces, if originally well fitted and of homogeneous material, and if kept in good order, exhibit uniform intensity of pressure throughout, when the resultant pressure passes through the centre of figure, and sustain uniformly varying pressure when the resultant is outside that centre. In the latter case, the *mean* pressure may generally be assumed as a uniformly distributed pressure in calculations. Inequality of pressure leads, first, to unequal wear, then to exaggerated variation of intensity of pressure, and finally to "cutting," or abrasion, and destruction of the wearing parts. The maximum permissible intensity of pressure is generally the less as the speed of rubbing is the greater, and is usually but a small fraction of that representing the "elastic limit" of the metal resisting it.

Plane surfaces subject to wear under a motion of rotation, even where the pressure is at first uniformly distributed, are apt ultimately to take such form that the pressure is of varying intensity. The method of variation will be dependent upon the form, and the fitting of the journal to its bearing. As an example, a disk rotating about its centre will usually wear differently at the periphery and toward the centre, and thus ultimately is caused such a distribution of pressures as will throw the greater part of the load upon the central part of

the disk. The tendency is usually to effect such a distribution of pressures as will finally give permanence of form.

Curved surfaces may thus take pressure in many ways; but it probably rarely occurs in practice that the pressure is of perfectly uniform intensity. A number of cases will be considered in the succeeding articles. The most important case is the following:

A cylindrical or spherical journal, if perfectly fitted, when unloaded will, with its bearing, take such a form under load that the intensity of pressure on the bearing surface will vary as the cosine of the angle made by a radius passing through the given point in that surface with that radius with which the resultant pressure coincides. Thus:

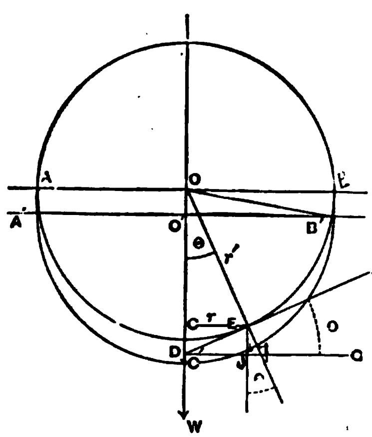

FIG. 9.—DISTRIBUTION OF PRESSURE.

In the figure, let *ACB* be the trace of the bearing surface of a perfectly fitted unloaded journal. When the load comes upon it, the journal will sink a minute distance, OO', CC', into the bearing, slightly compressing the metal, and taking the new position $A'C'B'$. As the maximum intensity of pressure in any well-proportioned journal is usually but a small fraction of that which would produce a compression exceeding the elastic limit of the metal, and as within that limit the resistance is directly proportional to the compression, every part of the surface, as E, will be subject to pressure of intensity proportional to the displacement, EI, of that point in the bearing. Thus the pressure at B remains, as at first, zero, and contact simply is preserved; at E the pressure is proportional to EI, and at C to CC'. But the vertical displacement, CC', BB', EJ, is at all points the same, and the compression, EI, at any point, E, being very small, is measured by the product of that constant quantity into the cosine of the angle, $COE = \theta$, between the radius, OE, pass-

ing through that point, and the line of the resultant bearing pressure, OC.

The sum of all vertical components of these normal pressures, each of which latter is measured by the product of a constant into $\cos\theta$, is equal to the total load, W. Hence, taking the intensity of pressure at any point, E, as represented by p, and the constant as $p_{,}$, the pressure on any element, ds, is pds,—assuming the length of the element unity,—and this is equal to $p_{,}\cos\theta ds$. The vertical component, w, is

$$w = p\cos\theta ds = p_{,}\cos^2\theta ds;$$

and the total load and the value of $p_{,}$ are

$$W = p_{,}\int \cos^2\theta ds; \qquad p_{,} = \frac{W}{\int \cos^2\theta ds}.$$

But $\cos\theta = \frac{r'}{\sqrt{r_{,}^2 - r^2}}$, and $ds = \frac{dr}{\cos\theta} = dr\sec\theta$; then

$$W = p_{,}r_{,}\int_0^{r_{,}} \frac{dr}{\sqrt{r_{,}^2 - r^2}} = p_{,}r_{,}' \sin^{-1}\frac{r}{r_{,}} = 1.57\, p_{,}r_{,}; \quad (1)$$

$$p_{,} = \frac{W}{1.57 r_{,}}; \quad \ldots \ldots \quad (2)$$

and the pressure on unity of area, at any point, E, is proportional to $\cos\theta$, and is

$$p = \frac{W\cos\theta}{1.57 r_{,}}. \quad \ldots \ldots \quad (3)$$

when $r_{,}$ is the radius of the journal.

It is evident that a similar demonstration applies to the case of the sphere. The amount of compression is determined by the magnitude of the modulus of elasticity of the softer metal of journal or bearing, and by the intensity of pressure. Thus, for a maximum pressure of 1000 pounds per square inch

(703 kgs. per sq. cm.), a pressure often attained with steel crank-pins, and with a modulus of elasticity of the bronze bearing of 12,000,000 (843,600 kgs. per sq. cm.), the maximum compression would be but $\frac{1}{1200}$th the thickness of the "brass," or, for journals of small size, about 0.00004 inch (0.0001 cm.). This distribution of pressure remains constant so long as the maximum pressure is less than that producing wear.

In all cases which are to be here considered, W is the resultant pressure on the bearing surface. It is found by combining the weight of the parts carried by the journal with the effort acting upon the journal, directly or indirectly, and producing or tending to produce motion. The distribution of pressure under light loads and at high speeds is sometimes determined by the action of the lubricant, as illustrated in experiments with the "oil-bath." This treatment is exact for cylindrical shell-bearings in rigid frames, approximate only for other cases. This investigation exhibits plainly the desirability of securing the greatest possible rigidity of frames carrying bearings.

29. **The Friction of "Journals,"** as a source of lost work, is of great importance to the engineer. A journal is a surface of revolution, turning, loaded with a pressure due the weight of the shaft and its load, within another surface of revolution, called the "bearing," which should be of the same form, and which should perfectly fit the journal without pinching. These surfaces are almost invariably cylindrical; but they are sometimes conical, sometimes conoidal or ellipsoidal, and rarely of other related forms. Axle or shaft journals, gudgeons, and trunnions are the familiar forms of this element of mechanism.

A journal in thoroughly good order will fit the bearing throughout the arc of intended contact: it is the custom with many experienced engineers, however, to "free" the bearing at the sides, leaving the two surfaces in contact only for about one half the total depth of the bearing-piece, i.e., over an arc of contact of 120°. Journals also frequently wear loose, and thus concentrate the load upon a limited area. Bearings are also sometimes bored out a very little larger than their journals, with a similar result. The theory of such cases is as follows:

(1) A loosely fitting journal, ABC, when at rest, will lie at the lowest point in its bearing; but, when moving will roll up the side until it begins to slide; it then retains this position so long as the coefficient of friction is unchanged, and rises and falls as the coefficient increases and diminishes, continually finding new positions of equilibrium.

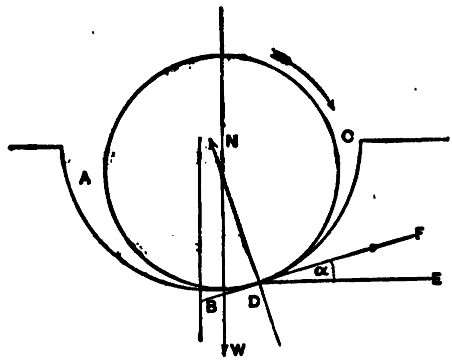

FIG. 10.—LOOSE BEARING.

At any one instant there are three forces in equilibrium: the weight, W, on the journal; the reaction, N, of the bearing; and the force of friction, holding the journal at the line of bearing on the inclined surface: this latter force is $F = fN$. The angle, $FDE = \alpha$, between the tangent to the common surface of contact and the horizontal is evidently that of an inclined plane on which the mass would slide with uniform velocity, and hence $\tan \alpha = f = \tan \varphi$. These forces being in equilibrium, they may be represented by the "triangle of forces," DNB.

Then, since the forces N and F are at right angles,

$$W^2 = N^2 + F^2;$$
$$= (1 + f^2) N^2; \quad \ldots \ldots \ldots \ldots \quad (1)$$

$$N = \frac{W}{\sqrt{1 + f^2}}; \quad \ldots \ldots \ldots \ldots \quad (2)$$

$$F = \frac{fW}{\sqrt{1 + f^2}} = \frac{W \tan \varphi}{\sqrt{1 + \tan^2 \varphi}} = W \sin \varphi; \quad . \quad (3)$$

and the motion of the journal carries it around, in the direction opposite to that motion, through the angle of kinetic friction, $\varphi = \tan^{-1} f$, as above stated.

The Moment of Friction is $M = Fr_1$, if r_1 represents the

radius of the journal, and the energy expended or work done is $U = aFr_{,}$, per unit of time, when a is the angular velocity. Hence this moment is

$$M = Wr_{,} \sin \varphi = \frac{fWr_{,}}{\sqrt{1 + f^2}}; \quad . \quad . \quad . \quad . \quad (4)$$

and the energy wasted, or work of friction, per minute or per second,

$$U = War_{,} \sin \varphi = \frac{fWar_{,}}{\sqrt{1 + f^2}}; \quad . \quad . \quad . \quad (5)$$

$$= 2W\pi nr_{,} \sin \varphi = \frac{2f\pi r_{,}}{\sqrt{1 + f^2}} Wn; \quad . \quad (6)$$

when n is the number of revolutions made in the unit of time.

(2) A perfectly-fitted bearing may be made by careful workmanship and fitting, while unloaded, when constructed; or it may be obtained by the wearing of the journal down into its bearing. In the first case, the pressure on the bearing gradually increases, as has been seen, from 0 at the diametral line to a maximum at the bottom, this pressure being at every point proportional to the elastic, radial, displacement of the surface where pressed. In the latter case the bearing wears until the sum of the vertical components of all such elementary pressures—which sum is equal to the load—is so adjusted as to check the wear, and this may give a distribution of pressures in any manner intermediate between the preceding case and one in which the pressure is uniform through the supporting "box," the latter value of the intensity of pressure being a limit which may be closely approached, or even actually attained.

For the first of these cases, the pressure on any elementary portion of the arc of the bearing, $d\theta$, is

$$N' = plr_{,}d\theta; \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad (1)$$

in which N' is the normal pressure on an elementary area, $lr_{,}d\theta$, which has the length of this journal, l, and the breadth

$r_1 d\theta$, p being the intensity of pressure at that part of the arc considered. The sum of all the vertical components of these normal pressures is equal to the load W. Then

$$W = \int_{\theta=-\frac{\pi}{2}}^{\theta=+\frac{\pi}{2}} plr_1 \cos\theta d\theta.$$

But the intensity of the pressure, p, will be zero at $\theta = \frac{\pi}{2}$, increasing as cosine θ to a maximum, p_1, at $\theta = 0$; therefore, since $p = p_1 \cos\theta$,

$$W = p_1 lr_1 \int_{\theta=-\frac{\pi}{2}}^{\theta=+\frac{\pi}{2}} \cos^2\theta d\theta; \quad \ldots \ldots \quad (2)$$

$$= p_1 lr_1 \left(\frac{\pi}{2} + \tfrac{1}{2}\sin\pi\right);$$

$$= 1.57 p_1 lr_1; \quad \ldots \ldots \ldots \ldots \quad (3)$$

$$p_1 = \frac{W}{1.57 lr_1}; \quad \ldots \ldots \ldots \ldots \quad (4)$$

$$p = 0.64 \frac{W\cos\theta}{lr'}; \quad \ldots \ldots \ldots \ldots \quad (5)$$

$$p \max = 0.64 \frac{W}{lr_1}. \quad \ldots \ldots \ldots \ldots \quad (6)$$

The intensity of the force of friction at any element is

$$fp = 0.64 \frac{Wf\cos\theta}{lr_1}; \quad \ldots \ldots \quad (7)$$

and, at $\theta = 0$, (fp) max. $= 0.64 \dfrac{Wf}{lr_1}$. $\ldots \ldots \ldots \ldots$ (8)

The total pressure on the bearing is

$$P' = 0.64W\int_{\theta=-\frac{\pi}{2}}^{\theta=+\frac{\pi}{2}}\cos\theta d\theta; \quad . \quad . \quad (9)$$

$$= 0.64W\,2\sin\frac{\pi}{2};$$

$$= 1.27W.$$

The total force of friction is

$$fP'W = 1.27fW; \quad . \quad . \quad . \quad . \quad . \quad . \quad (10)$$

and the work wasted is

$$U = fP's = 1.27fWs; \quad . \quad . \quad . \quad . \quad . \quad . \quad (11)$$

in which s is the distance traversed by the rubbing surface. Otherwise the moment of friction is

$$M = P'fr_1 = 1.27\,fWr_1; \quad . \quad . \quad . \quad . \quad (12)$$

and the energy lost is, per unit of time,

$$U = Ma = 1.27fWar_1 = 2.54fnr_1W\pi. \quad . \quad . \quad (13)$$

Hence, in a bearing thus fitted, if the unloaded journal is an absolutely perfect fit, the total friction is 1.27 times as great as with a loosely fitted journal.

(3) A bearing in which the journal is so grasped as to give uniform pressure throughout, produces a loss of power which is also easily calculated thus:

The intensity of pressure is at all points constant, and may be represented by p_1. The vertical component is $p_1\cos\theta$;

and the total weight, W, sustained by the journal is equal to the sum of all vertical components. The pressure on any element is $p_1 l r_1 d\theta$; its vertical component is $p_1 l r_1 \cos\theta d\theta$, and the total load is

$$W = p_1 l r_1 \int_{\theta_1 = -\frac{\pi}{2}}^{\theta_2 = +\frac{\pi}{2}} \cos\theta d\theta; \quad . \quad . \quad . \quad . \quad (1)$$

$$= 2p_1 l r_1; \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad (2)$$

$$p_1 = \frac{W}{2lr_1}. \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad (3)$$

Then the total pressure on the surface of the journal or of the bearing is the product of this intensity of pressure into its area, or

$$P' = p_1 l \pi r_1; \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad (4)$$

$$= \tfrac{1}{2}\pi W = 1.57W.$$

The total force of friction is

$$P'f = 1.57fW. \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad (5)$$

The moment of friction is

$$M = P'fr_1 = 1.57fWr_1; \quad . \quad . \quad . \quad . \quad (6)$$

and the work of friction is, per unit of time,

$$U = Ma = afP'r_1 = 1.57afWr_1; \quad . \quad . \quad . \quad . \quad (7)$$

$$= fnWr_1\pi^2; \quad . \quad . \quad . \quad . \quad (8)$$

i.e., it is 1.57 times as great as in the loosely-fitted journal, and 20 per cent. greater than in the last case.

The first of the three cases just considered is often met with, new journals being often purposely or carelessly bored to make a loose fit, and old journals often wearing loose. The second case arises when the journal is made an exact fit, when new and unloaded; and the last occurs when it has been running smoothly and without jar, and has thus gradually worked down into the bearing and has worn all portions of its surface to a small but usually appreciable extent; such a journal is always found to be in excellent condition. The usual case in practice lies between these. The last case may be also met with in those rare cases in which a new journal has been fitted tightly into its bearing, and yet oftener where, as sometimes happens, the heating of the "brass" causes it to grasp the journal, closing over it so tightly as to cause as great heating on the sides as on the bottom. The Author has sometimes met with such action in his own experience, even with very large journals and bearings.

It is seen from the theory just developed that, while in any journal the total pressure and the total resistance at the surface of the journal are the same for any given load, whatever the size of journal, the moment of friction increases with the diameter of the journal, and the work lost varies in the same ratio. It will be also noted that, since the liability of a journal to heat varies directly as the intensity of pressure and as the amount of work done, and inversely as the area across which this heat can be discharged, the diameter of a journal does not within certain limits affect this phenomenon. This will be better shown in another chapter. The bearing should evidently be so proportioned that serious lateral pressures shall not be produced when in operation.

With a flooded journal, as where the oil-bath is used, the pressure is probably nearly always a maximum at the meridian line, becoming zero at the edges of the brass. The second case is therefore correct here.

(4) The quantity of heat produced by the friction of the journal, in the several cases above treated, is obtained by dividing the work of friction by the mechanical equivalent of heat. Calling this J, and its reciprocal A, we have for the loose bear-

ing, Case 1, H representing the heat produced in the minute or the second, whichever may be the unit of time.

$$H = \frac{U}{J} = AU = 2AW\pi nr_1 \sin\varphi;$$

$$= 2AW\pi nr_1 \frac{f}{\sqrt{1+f^2}}. \quad . \quad . \quad . \quad (1)$$

For the second case, that of the perfectly fitting bearing,

$$H = 1.27AWafr_1 = 2.54AWfn\pi r_1; \quad . \quad . \quad (2)$$

and for the last case, that of a tightly fitted bearing and uniform pressure,

$$H = 1.57AWafr_1 = AWfn\pi^2 r_1. \quad . \quad . \quad . \quad . \quad (3)$$

(5) The power demanded to drive the journal against its own friction, i.e., the power lost at the journal, is measured in horse-power by dividing the work thus done per minute or per second by the value of the horse-power, i.e., by 33,000, or 550 foot pounds, or by 4500, or 75 kilogrammetres.

(6) A cylindrical journal turning in V's is a rare but not unknown case. Let ADB be such a bearing: let C be the shaft revolving in the direction of the arrow. It is evident that the shaft will tend to rise on the side A, and to relieve the side B from part of its weight. Hence the normal pressures N and N' will not be equal. The normal pressures N and N', combined with the frictional forces F and F', will give the component forces, Q and Q', respectively at the points A and B,

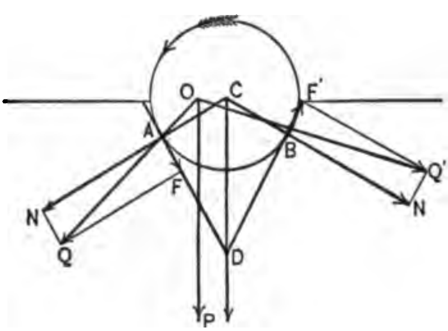

FIG. 11.—FRICTION IN V'S.

and these two forces must be in equilibrium with the force P acting through the shaft. Then, since NAQ, $N'BQ' = \varphi$, $QOP = NCP - \varphi$; $Q'OP = N'CP + \varphi$. Calling NCP and $N'CP$ equal to α, $QOP = \alpha - \varphi$ and $Q'OP = \alpha + \varphi$.

From the triangle of forces formed by Q, O, and P,

$$Q = P\frac{\sin(\alpha - \varphi)}{\sin 2\alpha}; \quad Q' = P\frac{\sin(\alpha + \varphi)}{\sin 2\alpha};$$

which expressions give the normal pressures N and N', and thence the force of friction is found to be

$$F = (N + N')\tan\varphi,$$

$$= P\frac{\sin(\alpha - \varphi) + \sin(\alpha + \varphi)}{\sin 2\alpha}\cos\varphi\tan\varphi = P\frac{\cos\varphi\sin\varphi}{\cos\alpha}.$$

Where the friction is slight the angle φ will be small, and $\cos\varphi$ may be taken equal to 1; then the value of the force of friction for a triangular bearing will become

$$F = P\frac{\sin\varphi}{\cos\alpha}.$$

In an ordinary free journal, however, this friction is

$$F = P\sin\varphi.$$

Hence the friction of a triangular journal is $\frac{1}{\cos\alpha}$ greater than in a free cylindrical journal.

If $ADB = 60°$, $\alpha = 60°$ and $\frac{1}{\cos\alpha} = 2$, or the friction of such a journal would be twice that of a journal bearing on the bottom of the "brass."

For $\alpha = 90°$, or when the shaft bears on opposite sides, $\frac{1}{\cos\alpha} = \infty$, and the friction is infinite. For the case of a close-fitting journal, or one bearing at all points of the brass,

$$F = P \sin\varphi \frac{\text{arc } AD}{\sin\alpha}.$$

If $\alpha = 90°$, $\sin\alpha = 1$, and $AD = 1.57$; hence the friction is $F = 1.57P \sin\beta$, or 1.57 times greater than that of a free bearing, as before found. For $\alpha = 30°$, or when the axle bears only on $\frac{1}{6}$th of its circumference, we have $\sin\alpha = 0.500$ and arc $AD = 0.5236$, and $F = 1.0472P \sin\varphi$, or only 1.047 times that of a free bearing.

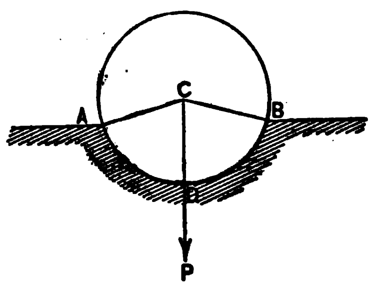

FIG. 12.—FRICTION OF JOURNAL.

When α, is very small the arc $AD = \sin\alpha$, and the formula reduces to $P \sin\varphi$, or the friction for a free bearing.

The Length of Journal may be determined when the conditions giving a measure of the resistance and work of friction are known, and is evidently nearly independent of the diameter; since a variation of diameter but slightly affects f, and hence does not greatly affect the value of the quantity of work pVf, upon the value of which the work done on the unit of area, and therefore the working of the journal, mainly depends. The intensity of pressure, p, being reduced by enlarging the journal, the velocity V is correspondingly increased. A limit to length of journal is usually fixed by assuming a safe value for that product, as 60,000 for well-made crank-pins, 40,000 for locomotive-pins, or for journals well protected from dust and on which the pressure is unintermitted. This principle may be shown thus: The work of friction is $fP_m n\pi d = U$; the projected area subjected to pressure is equal to $A = ld$, and

the work per unit of this area being taken, as a mean, at 50,000f foot-pounds, 600,000 inch-pounds, is

$$\frac{U}{ld} = fP_m\pi\frac{nd}{ld} = fpm\pi\frac{n}{l};$$

i.e.,
$$600{,}000f = fP_m\pi\frac{n}{l};$$

$$l = \frac{P_m\pi n}{600{,}000} = 0.000005Pn;$$

$$p = \frac{600{,}000}{\pi nd} = \frac{50{,}000}{V}.$$

If we give the diameter a fixed relation to length, i.e., $l = ad$,

$$P = pld = ad^2; \qquad d = \sqrt{\frac{P}{a}};$$

while the diameter, calculated for strength against breaking, as in an end journal, is

$$d \propto \sqrt{\frac{aP}{R}},$$

where R is the modulus of rupture. Then

$$d = b\sqrt{\frac{aP}{R}} = \sqrt{\frac{P}{ap}};$$

$$a = \sqrt{\frac{R}{b^2p}} = \sqrt{\frac{RV}{50{,}000b^2}};$$

and

$$a = c\sqrt{RV} = e\sqrt{\frac{R}{p}};$$

in which $c = 0.0007$ to 0.0009 for marine engine crank-pins, or $c = 0.0004$ for locomotives, and $e = 0.05$ to 0.06 and $e = 0.08$. Journals carrying unintermitted loads require longer pins.

The pressure on journals is very generally reckoned, as above, by reference to the projected area.

A Line of Shafting consists of a succession of iron or steel shafts, or axles, connected end to end by "couplings," and carrying often a set of pulleys or of gearing, by which the power transmitted to and through the line is distributed to the driving shafts of various machines. This is called "line-shafting," to distinguish it from the "countershafts" and other shafting of special machines.

Line-shafting is carried by a succession of bearings placed 40 to 60 diameters of the shafting apart usually, and the journals are generally made three or four diameters in length. These journals sustain the weight of the shafting, pulleys, and belting, and the resultant pull of the belts, and are thus subject to considerable friction and consequent waste of power. Since the power applied is all received at the end, it is evident that the size of the shafting may be economically reduced, as this power is distributed to the machinery driven in passing from the receiving to the farther end.

Were this variation to be made by a gradual reduction of diameter, and were the power all transmitted to the farther end, the economical method of proportioning would involve the measurement of the friction, and the determination of such a size as would be the minimum required safely to transmit the effort demanded to overcome the friction beyond the given point, and to deliver the needed power.

Resistance to torsion varies as the cube of the diameter of the shaft. Calling the diameter d, the moment safely applicable to the shaft is

$$M = Ad^3, \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad (1)$$

when A is a coefficient correct for the given case, and varying with the material and the magnitude of the factor of safety, which latter quantity ranges all the way from 6 to 30 in common practice.

If the weight of the material of which the shafting is composed be called w, the weight of a unit of length is

$$w' = 0.7854wd^2; \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad (2)$$

and its friction, nearly

$$fw' = 0.7854fwd^2. \quad . \quad . \quad . \quad . \quad . \quad . \quad (3)$$

The moment of friction is

$$fw'\frac{d}{2} = 0.3927fwd^3; \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad (4)$$

and the "exhaustive length," as it is called by Rankine, which would be just sufficient to take up the whole applied moment, by its friction, is

$$L = \frac{A}{0.3927fw}; \qquad A = 0.3927fwL. \qquad (5)$$

Then the maximum resistance of the shafting is Ad^3; the moment of friction per unit of length is $Bd^3 = 0.3927fwd^3$; and the moment demanded to turn a tapering line of shafting proportioned for minimum loss of power is

$$Ad^3 = 0.3927fwLd^3 = M_0 + 0.3927fw\int d^3dx,$$

$$= M_0 + B\int_0^x d^3dx, \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad (6)$$

when x is measured from the end farthest from that at which the effort is applied. Taking $x = 0$ at the nearer end,

$$Ad^3 = B\int_x^0 d^3dx + M_0; \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad (7)$$

M_0 being the useful moment transmitted. Then calling $d = y$,

$$3Ay^2dy = By^3dx;$$

$$3\frac{A}{B}\int_{d_0}^{d_1}\frac{dy}{y} = \int_{l_1}^{0} dx;$$

$$\frac{3A}{B}\left(\log_e d_1 - \log_e d_0\right) = -l; \quad . \quad . \quad . \quad . \quad (8)$$

where d_1, d_0, are the diameters of the shafting at the ends and l the total length; hence

$$3\frac{A}{B}\log_e\frac{d_1}{d_0} = -l_1;$$

$$d_1 = d_0 e^{-\frac{Bl_1}{3A}};$$

$$= d_0 e^{-\frac{l_1}{3L}}. \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad (9)$$

The diameter thus diminishes by a geometrical ratio, the variation of diameter of section of the shafting being represented by a logarithmic curve.

When the shaft is reduced, as is usual, by sections, each having a fraction, m, of the length of the whole line, the diameters diminish in a geometrical progression having the ratio

$$\left(1 - \frac{ml_1}{L}\right)^{\frac{1}{3}}.$$

The work of friction on the line having a continuously reduced section is

$$U = Ba\int_0^x d^2dx,$$

$$= Bad_0^2\int_0^{l_1} e^{-\frac{Bx}{3A}}dx,$$

$$= 3Aad_0^2 e^{-\frac{Bl_1}{3A}} + 3Aad_0^2, \quad . \quad . \quad . \quad (10)$$

in which a is the angular velocity of the shafting.

30. The Friction of Pivots, often used to sustain the "end-thrust" of shafting, is of the same character as that observed in the usual forms of journal, but the forces are somewhat differently distributed. A journal sustains a load applied in the plane of revolution of a shaft; a pivot meets the resistance due to longitudinal pressures, and is usually a circular plane surface at the end of the shaft subjected to such "thrust." When the thrust is received by annular plane surfaces formed on "collars" moving with the shaft and resting on similar annular surfaces forming bearings, the theory is the same as for the plane pivot. Pivots are sometimes made conical and sometimes of spherical surfaces; they are occasionally given the form of a surface of revolution generated by the revolution of the tractrix.

(1) The "Circular Plane Pivot" is not one of stable form. The velocity of rubbing increases from zero at the centre to a maximum at the periphery, and, assuming the intensity of pressure originally uniform over the whole surface, the tendency is to wear on the outer parts and to throw more and more pressure on the central portions, finally bringing the surface to a much more stable form, but to one which is probably rarely the same for any two cases.

Assuming the intensity of pressure to be p, the total load to be W, and the radius to be r, let $\dfrac{W}{\pi r_1^2} = p'$ be the same throughout; the normal pressure on any elementary ring, of the radius r and width dr, is

$$N = 2p'\pi r dr; \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad (1)$$

the elementary moment of friction is

$$fNr = 2fp'\pi r^2 dr. \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad (2)$$

The total moment of friction is

$$\begin{aligned} M &= 2fp'\pi \int_0^{r_1} r^2 dr, \\ &= \tfrac{2}{3} fp'\pi r_1^3, \\ &= \tfrac{2}{3} fWr_1; \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad (3) \end{aligned}$$

and the energy lost in the unit of time is

$$U = Ma = \tfrac{2}{3}afWr_1 \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad (4)$$

symbols as before.

Hence the resistance and the work of friction on the flat pivot may be considered as due the total load, resting on a pivot at a distance from the centre equal to two thirds the radius of the disk. This expression is equal to

$$U = Ma = \tfrac{4}{3}\pi fWr_1n; \quad . \quad . \quad . \quad . \quad . \quad (5)$$

when n is the number of revolutions made in the unit of time.

(2) The "Collar-Bearing" is a plane pivot, of which the central portion is removed; its moment of friction is therefore obtained by integrating the expression just given for the flat pivot between the limits of the two radii R_1 and R_2 of the collar. Thus

$$M = 2fp'\pi \int_{r_1}^{r_2} r^2 dr;$$

$$= \tfrac{2}{3}fp'\pi\,(r_2^3 - r_1^3);$$

$$= \tfrac{2}{3}fW\frac{r_2^3 - r_1^3}{r_2^2 - r_1^2}. \quad . \quad . \quad . \quad . \quad . \quad (1)$$

The work wasted by friction is

$$U = Ma = \tfrac{2}{3}afW\frac{r_2^3 - r_1^3}{r_2^2 - r_1^2}. \quad . \quad . \quad (2)$$

These expressions reduce to those for the pivot when r_1 is made zero.

In the case of the collar, the "mean lever," as it is called, which is $\tfrac{2}{3}r_2$ for the pivot, becomes equal to

$$\frac{r_1 + r_2}{2} + \frac{(r_2 - r_1)^2}{12r_1} = \frac{6r_1(r_1 + r_2) + (r_2 - r_1)^2}{12r_1}.$$

The expression for energy lost reduces also to

$$U = \tfrac{2}{3}\pi f n W \frac{r_2^{\,3} - r_1^{\,3}}{r_2^{\,2} - r_1^{\,2}}, \quad . \quad . \quad . \quad . \quad . \quad . \quad (3)$$

when the number of revolutions, n, made in the unit of time is introduced.

(3) The "Conical Pivot" is made by shaping the end of the axle into a cone and fitting to it a bearing of similar form. In this case the normal pressure on the bearing surface instead of being equal to the total load, W, is increased in the proportion of radius to the sine of the angle of inclination of the cone, i.e., the half-angle of the cone. Calling this angle α, and resolving the force, W, into components, N, normal to the inclined surfaces of the cone, we have

$$2N \sin \alpha = W; \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad (1)$$

$$N = \frac{W}{2 \sin \alpha}. \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad (2)$$

The friction-force is

$$F = 2fN = f\frac{W}{\sin \alpha}; \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad (3)$$

its moment is

$$M = \tfrac{2}{3} f r_1 \frac{W}{\sin \alpha}. \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad (4)$$

Since the "mean lever" is two thirds r_1, and the work or energy wasted is

$$U = Ma = \tfrac{2}{3} a f r_1 \frac{W}{\sin \alpha}; \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad (5)$$

$$= \tfrac{4}{3}\pi r_1 f n \frac{W}{\sin \alpha}. \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad (6)$$

By reducing the length of the coned part embraced by the bearing, the intensity of the pressure is increased, but the moment and the work of friction are reduced as the cone bearing is decreased in depth; and it is thus possible, if the limits set by adhesion and abrasion are not passed, to make them less than with the plane pivot of usual proportions; although reducing the diameter of the latter to the same extent will give still greater efficiency, as is seen by making $\alpha = 90^\circ$ in the last expression above given. Conversely, a sharp-pointed pivot may have the friction and the lost work increased indefinitely by reduction of the angle α, and they become infinite, for $\alpha = 0$.

(4) A "Truncated Pivot" is a journal in the form of a truncated cone on the end of a shaft subject to thrust. Its friction, moment of friction, and work of friction are evidently the sum of those for the two parts into which it may be considered as naturally divisible; and

$$M = \tfrac{2}{3} f \frac{W(r_2^3 - r_1^3)}{r_2^2 \sin \alpha}; \quad \ldots \ldots \quad (1)$$

$$U = Ma = \tfrac{2}{3} af \frac{W(r_2^3 - r_1^3)}{r_2^2 \sin \alpha}; \quad \ldots \ldots \quad (2)$$

$$= \tfrac{4}{3} \pi fn \frac{W(r_2^3 - r_1^3)}{r_2^2 \sin \alpha}. \quad \ldots \ldots \quad (3)$$

The wear of this pivot will always in time throw the whole load on the flat face, provided that has area enough to carry it.

(5) A Conical Pivot, loaded transversely, as in the lathe "centre," is subject to the same laws as the common pivot; but since the load is at right angles to the axis, the expressions already given must be modified by substituting $\cos \alpha$ for $\sin \alpha$. Then

$$F = fW \sec \alpha; \quad \ldots \ldots \ldots \quad (1)$$

$$M = \tfrac{2}{3} fr_1 W \sec \alpha; \quad \ldots \ldots \quad (2)$$

$$U = Ma = \tfrac{2}{3} afr_1 W \sec \alpha; \quad \ldots \ldots \quad (3)$$

$$= \tfrac{4}{3} \pi r_1 fnW \sec \alpha. \quad \ldots \ldots \quad (4)$$

The heat produced by the friction of the flat pivot is

$$H = \frac{U}{J} = \tfrac{2}{3} A W a f r_1;$$

$$= \tfrac{4}{3} A W f n \pi r_1; \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad (1)$$

that of the collar-bearing is

$$H = \tfrac{2}{3} A W a f \frac{r_2^3 - r_1^3}{r_2^2 - r_1^2};$$

$$= \tfrac{4}{3} A W f n \pi \frac{r_2^3 - r_1^3}{r_2^2 - r_1^2}; \quad . \quad . \quad . \quad . \quad . \quad (2)$$

that of the conical pivot with end-bearing is

$$H = \tfrac{2}{3} A W a f \frac{r_1}{\sin \alpha}; \quad . \quad . \quad . \quad . \quad . \quad . \quad (3)$$

$$= \tfrac{4}{3} A W f n \pi \frac{r_1}{\sin \alpha}; \quad . \quad . \quad . \quad . \quad . \quad . \quad (4)$$

and when this pivot is truncated,

$$H = \tfrac{2}{3} A W a f \frac{r_2^3 - r_1^3}{r_2^2 \sin \alpha};$$

$$= \tfrac{4}{3} A W f n \pi \frac{r_2^3 - r_1^3}{r_2^2 - r_1^2}. \quad . \quad . \quad . \quad . \quad . \quad (5)$$

The same pivot loaded transversely gives

$$H = \tfrac{2}{3} A W a f r_1 \sec \alpha;$$

$$= \tfrac{4}{3} A W f n \pi r_1 \sec \alpha. \quad . \quad . \quad . \quad . \quad . \quad (6)$$

(6) A "Spherical Bearing," or a bearing composed of a portion of a spherical surface, is often used in mechanism, and especially for the "steps" of water-wheel shafts.

In such a case, if the bearing wears, as may often be the case, until the intensity of pressure, $p_{,}$, is uniform over its surface, or if it is so fitted originally, the pressure on any elementary ring of radius r, and so situated that its normal makes the angle θ with the axis of the shaft, is $2p\pi r ds$. But the breadth of the ring, ds, is equal to $dr \sec\theta$; hence the pressure on an elementary ring is $2p\pi r dr \sec\theta$; and the total pressure is obtained by integrating this expression after determining the values of p and of $\sec\theta$ in terms of r.

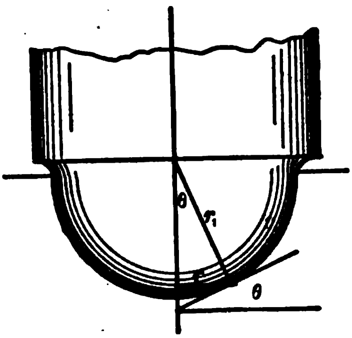

FIG. 13.—SPHERICAL STEP.

The value of p will be usually variable, and, for a common case, may be taken as 0 at the horizontal diameter, and a maximum at the lowest point in the "step," varying as the cosine of the angle θ. Then $p = p' \cos\theta$, and the total normal pressure is

$$N = 2p'\pi \int \sec\theta \cos\theta r dr = 2p'\pi \int_0^{r_1} r dr;$$

$$= p'\pi r_1^2. \quad \ldots \ldots \ldots \quad (1)$$

The total moment of friction is

$$M = 2fp'\pi \int_0^{r_1} r^2 dr;$$

$$= \tfrac{2}{3} fp'\pi r_1^3; \quad \ldots \ldots \ldots \quad (2)$$

and the work lost from this cause is

$$U = Ma = \tfrac{2}{3} afp'\pi r_1^3; \quad \ldots \ldots \ldots \quad (3)$$

$$= \tfrac{4}{3} \pi^2 fp' n r_1^3. \quad \ldots \ldots \ldots \quad (4)$$

To find p', in terms of the total load, W, we have the sum of all vertical components of the elementary pressures,

$$W = 2p'\pi \int_0^{r_1} \cos\theta \, r dr;$$

$$= 2p'\pi \int_0^{r_1} \frac{\sqrt{r_1^2 - r^2}}{r_1} r dr;$$

$$= \tfrac{2}{3} p' \pi r_1^2, \text{ nearly}; \quad . \quad . \quad . \quad . \quad . \quad . \quad (5)$$

whence

$$p' = \tfrac{3}{2} \frac{W}{\pi r_1^2}; \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad (6)$$

$$M = fWr_1; \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad (7)$$

$$U = Ma = afWr_1;$$

$$= 2f\pi n r_1 W. \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad (8)$$

(7) For a journal (Fig. 13) of spherical surface, not a complete sphere, like the common "cup and ball" pivot, but less than a hemisphere in extent, taking r_1 as the radius of the sphere, r_2 as the maximum radius of the projection of the bearing on the plane normal to the axis, we have, as before, for the elementary normal pressure, assuming the ***intensity*** of pressure variable as before,

$$n = 2p'\pi r dr;$$

for the moment of friction,

$$M = 2fp'\pi \int_0^{r_2} r^2 dr;$$

$$= \tfrac{2}{3} fp'\pi r_2^3. \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad (1)$$

For the work lost,

$$U = Ma = \tfrac{2}{3} afp'\pi r_2^3;$$

$$= \tfrac{4}{3} fp'\pi^2 n r_2^3. \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad (2)$$

Then, to find p',

$$W = 2p'\pi \int_0^{r_2} \cos\theta r dr;$$

$$= 2p'\pi \int_0^{r_2} \frac{\sqrt{r_1^2 - r^2}}{r_1} r dr;$$

$$= \tfrac{2}{3} p'\pi \frac{[r_1^3 - (r_1^2 - r_2^2)^{\frac{3}{2}}]}{r_1}; \quad . \quad . \quad . \quad . \quad (3)$$

$$p' = \tfrac{3}{2} \frac{W r_1}{\pi[r_1^3 - (r_1^2 - r_2^2)^{\frac{3}{2}}]}; \quad . \quad . \quad . \quad . \quad . \quad (4)$$

and, approximately,

$$M = fW \frac{r_2^3}{r_1^3 - (r_1^2 - r_2^2)^{\frac{3}{2}}}; \quad . \quad . \quad . \quad . \quad (5)$$

$$U = Ma = fW \frac{a r_2^3}{r_1^3 - (r_1^2 - r_2^2)^{\frac{3}{2}}};$$

$$= 2f\pi W n \frac{r_2^3}{r_1^3 - (r_1^2 - r_2^2)^{\frac{3}{2}}}. \quad . \quad . \quad . \quad (6)$$

(8) The heat developed by the friction of a spherical journal, measured in thermal units, is, for the hemisphere, nearly,

$$H = AWafr;$$

$$= 2AWfn\pi r; \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad (1)$$

and for the smaller surface it becomes nearly

$$H = AWaf \frac{r_2^3}{r_1^3 - (r_1^2 - r_2^2)^{\frac{3}{2}}};$$

$$= 2AWfn\pi \frac{r_2^3}{r_1^3 - (r_1^2 - r_2^2)^{\frac{3}{2}}}. \quad . \quad . \quad . \quad (2)$$

"Spherical" journals may usually be treated as bearing over the whole hemispherical surface in the manner described

in the examples just given. Where disks are used of which the surfaces are small portions of spheres of comparatively large radius, they may usually be safely treated as plane disks. They are often fitted to bear only near the centre, but wear soon gives them a larger area of bearing surface.

(8) The "Tractory" or "Tractrix" Pivot is a pivot of which the generatrix is Huygens' curve, the "tractrix." This curve was proposed for pivots by C. Schiele, by whose name it is often known. The curve may be described by affixing a pencil-point to a heavy weight, placing the pencil on the point of intersection of the proposed curve with the maximum proposed diameter of the pivot, attaching a string to the pencil, with a length equal to the maximum radius, and then drawing the free end of the string along the axis; the pencil-point will describe the tractrix. The tangent of this curve is evidently of constant length. The valuable property of the curve is that the wear due to friction is the same at all of the elementary rings into which the bearing surface may be conceived to be divided.

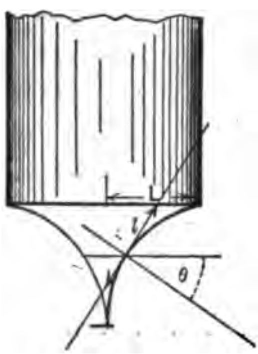

FIG. 14.—TRACTRIX.

Let θ represent the angle, at any elementary ring of the journal, between the tangent to the surface at that ring and the axis. Let r be the radius of that ring, and r_1 that of the pivot at the larger end of its bearing, and let l be the constant length on the tangent intercepted between the two rectangular axes bounding the curve. Then the area of any ring is $2\pi r ds = 2\pi r dr \operatorname{cosec} \theta$.

The normal pressure on that ring is (Fig. 14)

$$N = 2p_1 \pi r dr \operatorname{cosec} \theta = 2\frac{p_1 r dr}{\sin \theta};$$

its vertical component is

$$w = N \sin\theta;$$

$$= 2p_1 \pi r dr;$$

and the total load is

$$W = 2p_1\pi\int_0^{r_1} rdr = p_1\pi r_1^2;$$

and the intensity of the pressure is

$$p_1 = \frac{W}{\pi r_1^2};$$

and equal to that on a flat pivot, assuming in both cases that wear has uniformly distributed it.

The resistance due to friction on any elementary ring is

$$fN = 2fp_1\pi rdr \operatorname{cosec} \theta;$$

the moment is then

$$fNr = 2fp_1\pi r^2dr \operatorname{cosec} \theta;$$

$$= 2fp_1\pi r^2\frac{dr}{\sin\theta} = 2fp_1\pi r^2\frac{l}{r}dr;$$

$$= 2lfp_1\pi rdr.$$

The total moment of friction is

$$M = 2lfp_1\pi\int_0^{r_1} rdr = l.fp_1\pi.r_1^2;$$

which, when $r_1 = l$, and the pivot is thus given maximum supporting area, becomes

$$M = r_1^3fp_1\pi = fWr_1.$$

The energy wasted is

$$U = Ma = afp_1r_1^3\pi = 2\pi^2r_1^3fp_1n = 2f\pi r_1Wn;$$

when n is the number of revolutions per second.

The heat produced is

$$H = 2Af\pi^2 r_1^3 p_1 n = 2\pi A f r_1 W n.$$

The moment of friction with this pivot is thus equal to the product of the load, the coefficient of friction and the maximum radius, and is one half greater than that of the flat pivot. Its advantage is considered to be found in the distribution of pressure and its regular wear. Its moment of friction is independent of the length of the pivot. This pivot is sometimes called the "anti-friction" pivot.

31. The Friction of Cords, and of Belts or Bands, is usually intended to be a friction of rest. Where transmitting power, this is almost invariably the case; where the band or cord forms a part of or acts the part of a brake, the friction is that of motion. The principles are precisely the same for both cases, the coefficient of friction merely having a different value. The cord is almost invariably wrapped about a cylinder.

When a flexible cord or band is wound around a cylinder, an effort being applied at one end and a resistance at the other, the total effort producing equilibrium or motion must equal the sum of the resistance and of the friction of the cord on the surface which it traverses; while, if the applied force simply prevents motion, it is equal to the difference between the other two forces, friction always acting to prevent movement. The magnitude of the total resistance offered by the force of friction is determined by the intensity and method of variation of the normal pressure between the band and the cylinder, and by the value of the coefficient of friction.

(1) The intensity of the normal pressure at any point between the band and the cylinder is proportional to the tension of the band at that point. This is easily shown in several ways. Thus:

Assume the cylinder to have a length unity, the band to enwrap one half its circumference, and to be frictionless. Then, the total of all normal elementary pressures throughout the band resolved, each into components parallel to the two

ends, P_1Q_1 (Fig. 15), of the band, is equal to the sum of the two tensions at Q_1 and P_1; and

$$Q_1 + P_1 = 2P_1 = 2p_1r_1\int_0^\theta \cos\theta d\theta = 2p_1r_1 \sin\theta;$$

when p_1 is the intensity of normal pressure and θ is the angle, FOD, between the radius to the point of contact and the radius normal to the tangent coincident with the "leading part," CP_1, of the cord. Hence, if T is the tension and $\theta = \frac{\pi}{2}$,

$$T = P_1 = p_1r_1 \sin\frac{\pi}{2} = p_1r_1;$$

$$p_1 = P_1 \div r_1 = T \div r_1; \quad . \quad . \quad (1)$$

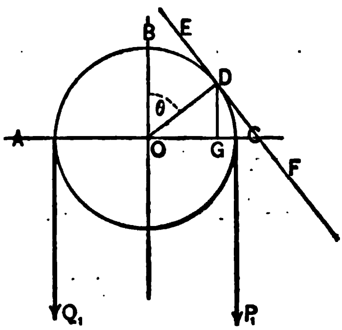

FIG. 15.—PRESSURE OF BELT.

and p_1 which is proportional to the tension of the band.

It is now evident that on a band subject to friction the pressure at every point in the circumference is proportional to

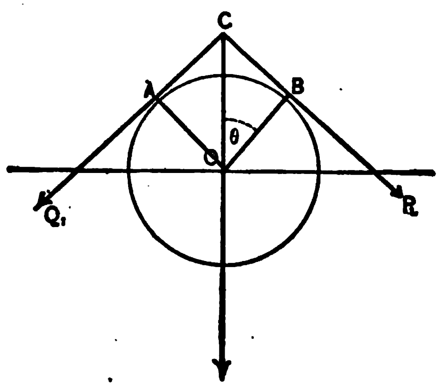

FIG. 16.—PRESSURE OF BELTS.

the tension of the band at that point; since, considering any one point, this is true; and the varying friction on either side

does not affect its equilibrium. It follows also that on belts subject to friction the pressure on the pulley under the band is variable, increasing from the side at which motion is resisted to the side at which the effort to produce motion takes effect, precisely in the proportion in which the tension on the band increases.

The same proposition may be proven thus: Draw intersecting tangents, BP_1, AQ_1, at any points near each other on the circumference, and call the angles, BOC, AOC, each θ. Then the resultant of the two forces, Q_1, P_1, will be

$$R_1 = \sqrt{(Q_1^2 + P_1^2 + 2Q_1P_1)\cos(180^\circ - 2\theta)};$$

and if the points are very near together, we may take $Q_1 = P_1$ and

$$R_1^2 = 2P_1^2(1 - \cos 2\theta);$$

$$= 2P_1^2 . 2 \sin^2 \theta. \quad . \quad . \quad . \quad . \quad . \quad . \quad (2)$$

Making the intercepted arc indefinitely small, we have, at the limit, $\sin \theta = d\theta$, and the arc is $d\theta$, calling $P_1 = T$, the tension

$$R_1^2 = 2P_1^2 . 2d\theta^2;$$

$$R_1 = 2Td\theta;$$

$$p_1 = \frac{R_1}{2r_1d\theta} = T \div r_1. \quad . \quad . \quad . \quad . \quad . \quad (3)$$

(2) The Resistance of a Band or Cord to slipping on a cylinder, or of a belt on a pulley, is a logarithmic function of the two tensions. It is thus determined:

At any given point the difference of the tensions on the two sides of that point is the measure of the force of friction at that element of the cylinder, and, as shown in the preceding

proposition, this is proportional to the tension there existing. Then we have

$$dT = fp_1r_1d\theta = fTd\theta; \quad . \quad . \quad . \quad . \quad . \quad (1)$$

$$\int_{T_2}^{T_1}\frac{dT}{T} = f\int_0^{\theta}d\theta;$$

$$\log_e \frac{T_1}{T_2} = f\theta; \qquad \frac{T_1}{T_2} = e^{f\theta}; \quad . \quad . \quad . \quad . \quad . \quad (2)$$

and

$$F = T_1 - T_2 = P_1 - Q_1 = T_1(1 - e^{-f\theta}); \quad . \quad . \quad . \quad (3)$$

$$= T_2\left(e^{f\theta} - 1\right); \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad (4)$$

If $\quad \dfrac{T_1}{T_2} = \dfrac{P_1}{Q_1} = N,$

$\therefore$

$$T_1 = P_1 = \frac{F}{1 - e^{-f\theta}} = F\frac{N}{N-1};$$

$$T_2 = Q_1 = \frac{F}{e^{f\theta} - 1} = \frac{F}{N-1}; \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad (5)$$

The mean tension on the belt and its ratio to F are

$$\frac{T_1 + T_2}{2} = \frac{T_2(1 + e^{f\theta})}{2}; \qquad \frac{T_1 + T_2}{2F} = \frac{T_2(1 + e^{f\theta})}{2T_2(e^{f\theta} - 1)}.$$

Calling $\theta = 2\pi n$, in which n is the number of turns or the part of a turn which the band or cord makes around the cylinder, and reducing for common logarithms, calling the modulus M,

$$T = e^{f\theta} = 10^{2f\pi Mn} = 10^{2.7288fn};$$

since

$$M = 0.434294 = \frac{1}{2.302585};$$

$$e^{f\theta} = e^{f2\pi n} = 10^{0.434294f\theta} = 10^{2.7288fn};$$

and

$$\text{common log}\,\frac{T_1}{T_2} = 2.7288fn;$$

$$T_1 - T_2 = T_1(1 - 10^{-2.7288fn});$$

$$= T_2(1 - 10^{2.7288fn} - 1); \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad (6)$$

$$T_1 = \frac{F}{1 - 10}^{-2.729fn}; \qquad T_2 = \frac{F}{10^{2.729fn} - 1}. \quad . \quad (7)$$

For the quantity $2.7288fn$ may also be substituted $0.00758 f\theta$ when θ is expressed in degrees, and $0.434294f\theta$, if in circular measure, common logarithms being used in both cases.

The moment of friction is

$$M = Fr_1 = r_1(T_1 - T_2); \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad (1)$$

and the work done in the unit of time is, as a maximum,

$$U = Ma = ar_1(T_1 - T_2);$$

$$= 2\pi nr_1(T_1 - T_2); \quad . \quad . \quad . \quad . \quad (2)$$

or per revolution,

$$U = 2\pi r_1(T_1 - T_2). \quad . \quad . \quad . \quad . \quad . \quad . \quad (3)$$

The values of M and of U may be less than the above, but cannot be greater.

(3) In a "strap-brake" the band or strap is sometimes intended to slip, the tensions being just sufficient to control the load. In this case the value of f is that of the coefficient of friction for motion. Here motion occurs between strap and pulley, and heat is produced to the amount of

$$H = 2A\pi r_1(T_1 - T_2). \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad (4)$$

The work and the moment on a slipping-strap are always maxima; if not slipping, the moment may be anything less, as where the brake sustains at rest a small load.

The total friction-force is seen, both for the belt and the brake, to be independent of the size of the cylinder upon which it is coiled, and to depend solely upon the angular extent of the circumference embraced or upon the numbers of turns taken by the band, the ratio of tensions becoming rapidly greater as the strap is wound on; thus, if $f = 0.333$, as taken by Weisbach, we have

EXTENT OF WINDING.

θ	π	n		$e^{f\theta}$	$\frac{T_1}{T_2}$
$90° =$	$\frac{\pi}{2} =$	$\frac{1}{4}$	revolutions	$10^{0.2254}$	1.788
$180° =$	$\pi =$	$\frac{1}{2}$	"	$10^{0.4548}$	2.85
$360° =$	$2\pi =$	1	"	$10^{0.9096}$	8.121
$720° =$	$4\pi =$	2	"	$10^{1.8192}$	65.95
$1440° =$	$8\pi =$	4	"	$10^{3.6384}$	4349
$2880° =$	$16\pi =$	8	"	$10^{7.2768}$	18,914,800
$3650° =$	$10\pi =$	10	"	$10^{9.096}$	1,247,380,000

The total amount of work lost by friction in any case is, as has been seen $(T_1 - T_2)\,S$, when the space, S, traversed by the effort, T_1, is given.

(3) The Friction of a Cord or Belt passing over the edge of a rigid body is determined by the amount of the change of direction taking place at the angle supporting it, by the value of the coefficient of friction, and by the magnitude of the two forces acting on either side the edge. If the edge is sharp, the cord may be stretched with such force as to cut it, and the resistance then becomes greatly increased; but if the edge is smoothly rounded, and the cord perfectly flexible and uninjured, the case is that of the friction of a cord on a cylinder of very small radius, on which an arc is enwrapped by the cord equal to the angle included between the two parts of the cord or belt. The resistance due to friction has been seen to be independent of the radius of curvature of the arc, and it is evident that the case is precisely that already considered.

Hence the friction is

$$
\begin{aligned}
F = fR = T_1 - T_2 &= T_2(10^{2.729fn} - 1); \\
&= W(10^{2.729fn} - 1); \\
&= W(10^{0.00758f\theta} - 1); \quad . \quad . \quad . \quad (1)
\end{aligned}
$$

when W is the load and n and θ° are the measures of the angle in parts of a circumference and in degrees, respectively.

The value of the pulling force is then

$$
\begin{aligned}
P = T_1 = T_2 + F &= 10^{2.729fn}W; \\
&= 10^{0.00758f\theta}W. \quad . \quad . \quad . \quad . \quad (2)
\end{aligned}
$$

An approximate expression for the resistance of friction for small angles is obtained by taking it as

$$F = ((f + 1)P + W)\sin\frac{\theta}{2};$$

$$= (2 + f)W\sin\frac{\theta}{2}, \text{ nearly.} \quad . \quad . \quad . \quad . \quad . \quad (3)$$

Where several edges are met, as in the "rendering" of a chain over a barrel of polygonal section, the faces of the polygon being equal in length to the links, the total friction may be calculated by introducing the sum of the angles, θ, into the first of the above forms, (1), or by raising the last (3) to a power, n, equal to the number of angles, the ratio of $\frac{T_1}{T_2}$ thus increasing in a geometrical ratio:

$$P = W^n\left[(2 + f)\sin\frac{\theta}{2}\right]^n. \quad . \quad . \quad . \quad . \quad . \quad (4)$$

The work wasted is

$$FS = WS\,(10^{2.729fn} - 1). \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad (5)$$

The useful work is WS and the total work PS.

The following table gives the ratios of $P : W$ for arcs less than 300°. For larger arcs see the preceding table.

VALUES OF $\frac{T_1}{T_2}$ FOR BELTS AND CORDS.

Angle θ.			Values of f.			
Degrees, $\theta°$.	Circular Measure, θ.	Parts of Circumf., n.	0.2	0.3	0.4	0.5
			Values of $T_1 \div T_2$.			
30	0.52	0.08	1.11	1.17	1.23	1.3
45	0.79	0.13	1.17	1.27	1.37	1.48
60	1.05	0.17	1.23	1.37	1.52	1.69
75	1.31	0.21	1.30	1.48	1.69	1.92
90	1.57	0.25	1.40	1.60	1.87	2.19
120	2.09	0.33	1.52	1.88	2.31	2.85
150	2.62	0.42	1.69	2.19	2.85	3.70
180	3.14	0.50	1.88	2.57	3.51	4.81
210	3.67	0.58	2.08	3.00	4.33	6.25
240	4.19	0.67	2.31	3.51	5.34	8.12
270	4.71	0.75	2.57	4.11	6.59	10.55
300	5.24	0.83	2.85	4.81	8.12	13.70

32. The Friction of the Wedge, and of the Screw, which is essentially a wedge, and both of which are illustrations of the inclined plane, has already been given in principle.

(1) Applying these principles to the case of the wedge (Fig. 17), we have the weight, or force driving the wedge, equilibrated by the two lateral pressures and the frictional resistance to slipping on the sides; and, α being the angle of the wedge,

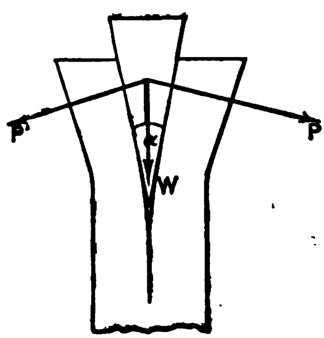

FIG. 17.—WEDGE.

$$W = 2P \sin\frac{\alpha}{2} + 2fP\cos\frac{\alpha}{2};$$

$$= 2P\left(\sin\frac{\alpha}{2} + f\cos\frac{\alpha}{2}\right). \quad . \quad (1)$$

When the wedge is forced back by the lateral pressures,

$$W = 2P\left(\sin\frac{\alpha}{2} - f\cos\frac{\alpha}{2}\right). \quad . \quad . \quad . \quad . \quad (2)$$

For other cases, simple and obvious modifications of the theory of the inclined plane already given will suffice.

(2) For the screw, which is to be considered an inclined plane wrapped around a cylinder, the pitch of the screw measures the height, the circumference is the length of base, and the length of thread of screw per revolution is the length of the inclined plane. We may take α (Fig. 18) for the angle at the point of the wedge or inclined plane, r the radius, p the pitch of the screw or the height of the inclined plane, P the force applied at the end of the lever-arm r, W the load, and N the reaction at R normal to the plane. Then, resolving parallel and perpendicular to the plane, we have

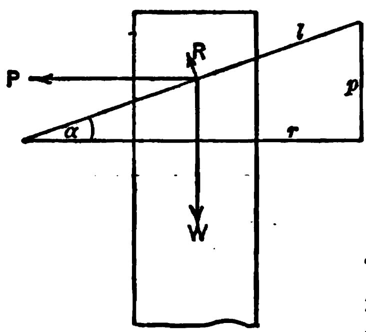

FIG. 18.—SCREW.

$$P\cos\alpha \pm fN - W\sin\alpha = 0;$$
$$P\sin\alpha - N + W\cos\alpha = 0;$$

and hence, for limiting values,

$$\frac{P}{W} = \frac{\sin\alpha \mp f\cos\alpha}{\cos\alpha \pm f\sin\alpha}. \quad (1)$$

The limits of value of the effort required at the end of a lever, or wrench, of the length r', is evidently

$$P' = P\frac{r}{r'} = W\frac{r}{r'} \cdot \frac{\sin\alpha \mp f\cos\alpha}{\cos\alpha \pm f\sin\alpha}. \quad . \quad . \quad (2)$$

The values of P and P' may be any values between the limiting values thus derived.

The case of the weight being raised by an active effort, P, is seen to be similar to that in which W acts to produce motion and P resists; the expression for the one being identical with that for the other, with the sign of f changed. The value of P is thus a maximum when an active and a minimum when a resisting force.

Friction-Couplings consist of a solid and a hollow cone, each

on the end of a shaft, and so fitted that they may be forced into contact, the one within the other, in such manner as to make a firm connection when desired. The lever-arm is, as has been seen (§ 30),

$$r = \frac{2}{3}\frac{r_1^3 - r_2^3}{r_1^2 - r_2^2},$$

and the intensity of pressure is

$$p = \frac{W}{A(\sin \frac{1}{2}\alpha + f \cos \frac{1}{2}\alpha)};$$

when W is the total effort, A the area of common surface of contact, and α the angle of the cone. Then the resistance due to friction is

$$F = fpA = \frac{fW}{\sin \frac{1}{2}\alpha + f \cos \frac{1}{2}\alpha};$$

$$p \text{ max.} = \frac{W}{fA}; \qquad P \text{ max.} = pA = \frac{W}{f};$$

and the limit becomes*

$$F \text{ max.} = fAp \text{ max.} = W.$$

For the plane disk, $\quad F \text{ max.} = fW.$

33. The Friction of Gearing is partly due to sliding of the teeth upon each other, and partly to resistance to rolling.

That part of the work lost by sliding is measured thus: Let α and β be the angles made by the directions of motion of the two teeth engaged with the normal to their surfaces at the line of contact, and let P be the intensity of the normal pressure. Then the resistance to sliding will be

$$R = fP. \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad (1)$$

---

* See Weisbach, vol. iii.

The work done against this friction will be, if s is their relative motion,

$$U = Rs = fPs = fP(v_1 \tan \alpha + v_2 \tan \beta)t, \quad . \quad . \quad (2)$$

when v_1 and v_2 measure the absolute velocities of the two teeth. Where several teeth are engaged,

$$U = \Sigma Rs = \Sigma fPs. \quad . \quad . \quad . \quad . \quad . \quad . \quad (3)$$

The loss of work and energy by friction of the teeth of gearing may be also measured thus:

Let the angular velocities of two teeth in contact be a', a'', and call the distance of the line of contact from the pitch-point of either tooth, s'. Then the relative velocity of rubbing is $v' = (a' + a'')s'$, and the work expended in friction is

$$U = fPv't = fPs'(a' + a'')t. \quad . \quad . \quad . \quad . \quad (4)$$

The loss due to rolling resistances is usually so small that it may be neglected; but the method of calculation is given in Art. 25.

In *Screw Gearing*, in which a screw or "worm" revolving in the plane of the gear drives the latter by engaging tooth after tooth as they come around, the loss of work is mainly due to sliding friction, and is often considerable. Here the resistance is, at the surface of the tooth,

$$R = fP. \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad (5)$$

The work lost is

$$U = Rs = fPs;$$

$$= fnP\sqrt{4\pi^2 r^2 + p^2}; \quad . \quad . \quad . \quad (6)$$

in which r is the radius of the worm and p the pitch, while n is the number of revolutions made in the given time.

When θ is the inclination of the worm-thread with the axis of the worm, the *total* resistance is

$$P' = R'\frac{1 + f \tan \theta}{\tan \theta - f}; \quad . \quad . \quad . \quad . \quad . \quad . \quad (7)$$

in which P' is the effort at the pitch-line tending to turn the worm, and R' is the resistance at the same point, but on the surface of the wheel, and in the plane of its rotation.

When we make $f = \tan \varphi$,

$$P' = R' \cot (\theta - \varphi). \quad . \quad . \quad . \quad . \quad . \quad . \quad (8)$$

The waste of power in worm-wheels is usually large—seldom less than one half, and often much more, as will be seen in a later chapter.

34. The Rigidity of Cordage and of Chains is due to the internal friction and distortion in the first, and to the friction of the links in the second case.

Coulomb, studying the resistance of pulleys and of cordage, was the first to appreciate the importance of that element which arises from the *stiffness* of the rope. He found experimentally that it consists of two parts, one of which is constant, while the other is variable with the load. Calling the constant part A, and the variable part bP, we have, as the total resistance due to stiffness, $A + bP$, of which A results from the natural stiffness of the cord, and the rest, bP, is due to the increase of stiffness consequent upon the added load, P.

Coulomb also found this resistance to vary inversely as the radius, or the diameter, D, of the pulley, and the total thus to vary as $\frac{A + bP}{D}$. He also found that the character of the material and the "lay" of the rope influenced this quantity seriously.

Thus the resistance increases with the increase of tension on the rope, and is measured by a constant number plus the tension multiplied by a constant coefficient. The resistance is also inversely as the radius of the pulley, sheave, or other cylinder on which the rope is wound, and as a function of the size of rope which appears to be variable with its character, material, and condition. This resistance is supposed to be due partly to the rigidity and molecular friction of the strands, but very largely, if not almost entirely, to the friction produced by the slipping of strand upon strand as the rope is bent and unbent in passing on and off the pulley.

35. The Laws governing the Rigidity of Cordage were determined by Coulomb, and the following approximate expressions for these laws were obtained by him:

$$R = d^2 \frac{A + bP}{D} \text{ for new white rope;}$$

$$R_1 = d^{\frac{3}{2}} \frac{A + bP}{D} \text{ for worn white rope;}$$

$$R_2 = d \frac{A + bP}{D} \text{ for packthread;}$$

$$R_3 = n \frac{A + bP}{D} \text{ for tarred ropes;}$$

in which expressions d is the diameter of the cord as below, n is the number of strands of tarred rope, and A and b are the quantities already given. R is the total added longitudinal resistance due to stiffness.

The work, W, in foot-pounds, performed in simply bending the rope, is measured by the product of the resistance just determined by the length (L) of that part of the rope which is "rendered" about the sheave or pulley; i.e.,

$$W = \frac{Ld^2}{D}(A + bP) \text{ for new white rope;}$$

$$W_1 = \frac{Ld^{\frac{3}{2}}}{D}(A + bP) \text{ for worn white rope;}$$

$$W_2 = \frac{Ld}{D}(A + bP) \text{ for packthread;}$$

$$W_3 = \frac{Ln}{D}(A + bP) \text{ for tarred rope.}$$

Weisbach proposes an expression for this resistance of simpler form than the above:

$$R = \frac{K + aP}{r};$$

in which K and a are coefficients to be determined by experiment; P is the pull on the rope, and r the radius of the pulley. His experiments were made with larger ropes than those of Coulomb.

Reuleaux uses a still simpler expression for belts running over smooth-faced pulleys:

$$R = \frac{aAP}{r},$$

in which R is the added resistance due to stiffness, as before; A the cross-section of the belt, P the pull, and r the radius of the pulley; a is an experimentally determined coefficient, which may be taken as 0.3 for leather, in British measure, or 0.012 in metric measures.

Eytelwein uses a similarly simple expression,

$$R = \frac{ad^2P}{r},$$

for the resistance due to rigidity of cordage, which expression may be used for ordinary work. For r in feet and d in "lines," $a = 18.6$, and the resistance, R, is expressed in pounds for common rope.

The constant coefficients given by Coulomb's experiment are as below. The unit of weight is the pound, that of length is the foot.

WHITE ROPE.

	Diameter in Inches.	Value of A.	Value of b.	Diameter in Inches.	Value of A.	Value of b.	
		lbs.			lbs.		
White Rope, New. Dry.	0.4	0.40	0.008	0.4	0.40	0.008	Dry. White Rope, Worn.
	0.8	1.61	0.032	0.8	1.14	0.053	
	1.6	6.44	0.128	1.6	3.22	0.064	
	3.2	25.75	0.511	3.2	9.10	0.180	
White Rope, New. Wet.	0.4	0.80	0.008	0.4	0.80	0.008	Wet. White Rope, Worn.
	0.8	3.22	0.032	0.8	2.28	0.053	
	1.6	12.88	0.128	1.6	6.43	0.064	
	3.2	51.51	0.511	3.2	18.20	0.180	

TARRED ROPE.

No. of Threads.	Weight per Foot. lbs.	Value of A.	Value of b.
6	0.02	0.15	0.008
15	0.05	0.77	0.020
30	1.01	2.53	0.040

Weisbach's coefficients are:

	British.	Metric.
For tarred rope,	$K = 3.31$; $a = 0.22$;	$K = 1.5$; $a = 0.006$.
For untarred rope,	$K = 0.19$; $a = 0.0645$;	$K = 0.086$; $a = 0.00164$.
For wire rope,	$K = 1.08$; $a = 0.094$;	$K = 0.49$; $a = 0.0024$.
For tarred wire rope and hempen core,	$K = 1.21$; $a = 0.037$;	$K = 0.57$; $a = 0.0007$.

The resistance of belts to flexure may be calculated by means of the simple formulas just given, and is expressed in terms of the tensions thus:

The resistance due to flexure is, according to Reuleaux,

$$R = \frac{aAP}{r}.$$

But the pull, P, is $\frac{T_1 - T_2}{2}$,

and $$R = \frac{(T_1 + T_2)aA}{2}\left(\frac{1}{r_1} + \frac{1}{r_2}\right), \quad . \quad . \quad . \quad . \quad . \quad (1)$$

when the whole circuit of the belt about both pulleys is taken, and when r_1, r_2, are their radii.

The work lost is then

$$U = Rs = \tfrac{1}{2}(T_1 + T_2)aAs\left(\frac{1}{r_1} + \frac{1}{r_2}\right); \quad . \quad . \quad . \quad (2)$$

a may be taken as already given.

36. The Friction of a Pulley or "Tackle" is due to two distinct phenomena: the friction of the pulley or "sheave" on its axis, i.e., the pin fixed in the "block," and the rigidity of the rope wound over the sheave. The first of these two resistances is that of the cylindrical journal.

The load being W, the added resistances due these two causes, reduced to a common line of resistance with W, being $F + S$, the total load becomes, for a single block,

$$P' = W + F + S. \quad . \quad . \quad . \quad . \quad . \quad . \quad (1)$$

The work done usefully will be Wh, where h is the distance traversed by the load, and the total work will be

$$P'h = (W + F + S)h. \quad . \quad . \quad . \quad . \quad . \quad (2)$$

The methods of calculating the magnitude of these several forms of resistance have been already given.

37. The Friction of a System of Pulleys is the sum of the frictions of all the elements of the system; but as the load transmitted from pulley to pulley or sheave to sheave between the weight and the "hauling part" is continually augmented by added frictional resistances, the relation of the one quantity to the other must be determined by ascertaining the relations of these quantities for each.

If the ratio

$$\frac{P'}{W} = \frac{W + F + S}{W} = C \quad . \quad . \quad . \quad . \quad . \quad (1)$$

for a single pulley be known, and if this ratio be determined for each pulley of the whole system, then the ratio, $\frac{\overline{P'}}{W}$, for the

system is obtained by the continued multiplication of these values of C, and is

$$\overline{C} = C_1 . C_2 . C_3 . C_4, \text{ etc.} \quad . \quad . \quad . \quad . \quad . \quad (2)$$

The final value of $\frac{\overline{P'}}{W}$ is then known, $\overline{P}$ being the value which exceeds the value of $\overline{P}$, in a similar but frictionless system, in the proportion in which $\overline{C}$ exceeds unity. The relation of the effort, $\overline{P}$, required to raise any given weight, W, in any frictionless system of pulleys may be experimentally determined from the relation of velocities of the hauling and the lifting parts. Thus, if these velocities are V and $\overline{V}$,

$$\frac{\overline{P}}{W} = \frac{V}{\overline{V}}; \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad (3)$$

since, friction aside, the power or energy exerted and absorbed is the same at both ends of the system and

$$\overline{P}\,\overline{V} = WV. \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad (4)$$

Then, friction being considered,

$$\frac{\overline{C}P}{W} = \frac{\overline{P}}{W}; \qquad \overline{C}P = \overline{P}. \quad . \quad . \quad . \quad . \quad . \quad (5)$$

The relations between the effort exerted and the resistance overcome in systems of tackles are given in all treatises on mechanics.

38. "**Rolling Friction,**" or more correctly, ***resistance to rolling***, is a consequence of the irregularities of form and the roughness of the surfaces of bodies rolling, the one over the other. Its laws are not as yet definitely established, in consequence of the uncertainty which exists in experiment as to how much of this resistance is due to roughness of surface, how

much to original and permanent irregularity of form, and how much to distortion under the load. The first of these quantities evidently varies inversely as radius: the second similarly, and the third as a function of the hardness and elasticity of the material of which the two bodies are composed. The total resistance, if the distortion does not exceed the elastic limit, is proportional to the load carried at the line or band of contact. In all actual cases the line of contact of two surfaces originally tangent and unloaded becomes a band, of which the width increases with the magnitude of the load and with the softness of the material.

"*Friction-Wheels*" are often used to reduce the loss of energy at a journal, when the load is small, its direction constant, and the angular velocity small. In such case the journal or "gudgeon" is supported on the periphery of two "friction-wheels," which are themselves supported on journals turning with an angular velocity less than that of the supported shaft, as the diameter of the journal is less than that of the friction-wheels. A single wheel is sometimes used, in which case the work lost by friction is reduced in the proportion

$$\frac{U_2}{U_1} = \frac{r_1}{r_2}, \qquad (1)$$

when U_1, r_1 are the work done and the radius of the journal as ordinarily mounted, and U_2 is the work done against friction when the friction-wheel is introduced; r_2 is the radius of the friction-wheel.

When two supporting wheels are used,

$$\frac{U_2}{U_1} = \frac{r_1}{r_2 \cos \frac{\alpha}{2}}, \qquad (2)$$

in which α is the angle at the main journal-centre, subtended by the two friction-wheel centres.

39. **The Laws of the Friction of Rolling** are as simply expressed as are those of sliding friction. It is customary to take this resistance as proportional directly to the load and inversely as the radius of the rolling cylinder or wheel. Experiment shows, however, that, with wheels capable of yielding somewhat under load, the square root of radius should be taken in the formula for rolling resistance.

The magnitude of the force of the friction of rolling is, therefore, at the axis, in the first case,

$$F = f\frac{W}{r}, \quad \ldots \ldots \ldots \quad (1)$$

in which f is the coefficient for the friction of rolling; W is the load on the line of contact; and r is the radius of the rolling cylinder or wheel. Here the effort is taken at the axis of the rolling body; acting at the circumference of the roller or wheel, as where straight-lined surfaces have relative motion on interposed rollers, the force of friction becomes

$$F = \tfrac{1}{2}f\frac{W}{r}. \quad \ldots \ldots \ldots \quad (2)$$

The first of these two cases is illustrated in ordinary vehicles, the second where a heavy mass on rollers has the hauling rope or chain attached to the mass itself. In the latter case, two frictional resistances are met—at top and at bottom of the roller. The moment of resistance is

$$M = Fr = fW.$$

The moment of friction is evidently thus measurable by the product of the load into an arm the value of which may be determined by experiment, and the resistance is thus plainly of the nature of a couple resisting rotation. This moment, multiplied by the relative angular velocity of the two surfaces, gives the work of rotation. The value of the arm as given by

Coulomb and Tredgold are from $f = 0.002$ foot with iron to $f = 0.006$ for hard wood; the load being multiplied by this arm the moment of resistance is obtained.

The work of rolling is evidently measured by

$$Ma = U = Fs = Wfs, \quad . \quad . \quad . \quad . \quad . \quad . \quad (3)$$

in which s is the space through which the carriage is drawn. The total work is this amount increased by the work of axle-friction, and that of raising the body against gravity in passing over the road.

Friction Gearing is sometimes used. It is made without teeth, the periphery of the wheel being sometimes plain, sometimes grooved, on the one shaft, and made of wedge-shaped section on the other, the one wheel driving the other by friction. In such cases the adhesion is usually found greater than is due to ordinary friction-coefficients.

In this case the work done against rolling resistance is measured by

$$U = abP; \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad (4)$$

where a is the relative angular velocity, b a constant depending on the conditions which affect rolling friction, and which will be given later; and P is the total pressure with which the two wheels are held together. It is evident that the pressure, P, must exceed the driving effort, P', in the proportion

$$\frac{P}{P'} = \frac{1}{f}, \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad (5)$$

or the surfaces will slip and the pair will refuse to drive.

With grooved wheels the pressure applied to hold them together may be reduced as the grooves are made with smaller angles. The value of f is, in this case, taken as that of the coefficient for rest; $f = 0.15$ as a minimum; $\frac{1}{f} = 7$.

40. **The Draught of Vehicles,** a case which illustrates the first of the two methods of application of the impelling force, for rolling friction is a matter demanding careful investigation. Morin and later investigators disagree in their statements of its laws. The former, who made very extended experiments, states these laws as follows:

(1) On hard surfaces, as paved and macadamized roads, the resistance is directly proportional to the weight of vehicle and load, inversely proportional to the diameter of wheel, and independent of the breadth of wheel-tire. It increases with velocity.

(2) On soft ground the resistance increases inversely as the breadth of tire. It does not sensibly vary with velocity. Morin concludes, also, that the line of draught should be horizontal.

Dupuit, working with carriages on macadamized roads, found the resistance to vary nearly inversely as the square root of the diameter of wheel, and directly as the load on the wheel. He found the resistance on pavement to be increased at high speeds by the concussions incident to rapid movement. Clark obtains a somewhat less simple law, which he expresses thus:

$$R = a + bv + \sqrt{cv}. \quad . \quad . \quad . \quad . \quad . \quad . \quad (1)$$

The work of hauling is then

$$U = Rs = (a + bv + \sqrt{cv})vt. \quad . \quad . \quad . \quad . \quad (2)$$

This formula is deduced from the experiments of Macneil on "metalled" roads.* The values of the constants for the several formulas expressing these variously stated laws are, in British measures, $a = 30$; $b = 4$; $c = 10$ pounds per ton, v being given in miles per hour; these figures are derived from Macneil's experiments.†

The resistance of all vehicles on common roads and streets

* Clark's Manual, p. 964.

† Parnell on Roads, p. 464.

is principally resistance to rolling, their axle-friction being usually comparatively small. The work of hauling is, then,

$$U = Fs = fWs = fWvt. \quad . \quad . \quad . \quad . \quad . \quad (3)$$

Railway trains are subject to the same laws as are carriages on hard roads, although some elements of resistance here enter which are absent in the latter case. Their wheels are fastened rigidly to the axles, which rotate with them and compel both wheels on the same axle to revolve with precisely the same angular velocity. In turning curves, or where, as is not infrequently the case, the wheels differ in size, this arrangement gives rise to an increased resistance, which is sometimes very considerable. This increase of resistance cannot occur when the wheels are loose on the axle, as on other vehicles. Another source of increased resistance is the friction of the flanges of the wheels rubbing laterally against the rails.

A principal resistance of trains at ordinary speeds is, however, as with other vehicles, that of rolling friction. The resistance of railway trains is commonly reckoned, in British measure, in pounds of resistance per ton of weight of train. Clark makes this resistance vary as a constant plus a term which varies as the square of the velocity, thus:

$$R = a + bv^2; \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad (4)$$

the values of the constants in which are given by Clark as $a = 6$ to $a = 8$; $b = \frac{1}{171}$ to $b = \frac{1}{240}$, the first set applying to whole trains, the second to train exclusive of engine.

The work of hauling is then

$$Rs = (a + bv^2)s = avt + bv^3t.$$

On the best roads the resistance is often one half that given above.

41. The Friction of Earth causes the retention of the form of elevations, or the preservation of embankments when soil is thrown up above the general level. The slope de-

pends usually upon the internal friction of the mass; and the steepness of a bank of earth cannot permanently exceed the minimum angle of repose of the material of which it is composed under the most unfavorable conditions, as when soaked by rains or floods.*

The resistance to displacement by sliding along any given plane, in such a mass, is equal to the normal pressure exerted between the parts of the mass on either side of that plane, multiplied by the coefficient of friction, i.e., the tangent of the angle of repose—of the material. Thus,

$$F = p_n \tan \varphi, \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad (1)$$

where F is the resistance per unit of area, and p_n is the intensity of pressure normal to the assumed plane.

In order that no part of a detached mass shall slide, it is thus necessary that the angle with the horizontal made by the plane along which least resistance to motion is offered shall be less than φ.

It is shown by Rankine, in the theory of the "Ellipse of Stress," † that the relation of maximum and minimum pressures must be such that

$$\sin \varphi > \frac{p_1 - p_2}{p_1 + p_2}, \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad (2)$$

and

$$\frac{p_1}{p_2} < \frac{1 + \sin \varphi}{1 - \sin \varphi}; \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad (3)$$

and hence that the ratio of their difference to their sum at any given point must not be greater than the sine of the angle of repose.

It is also shown ‡ that the intensity of pressure in a direction parallel to the surface must be

$$p_y = wx \cos \theta \frac{\cos \theta - \sqrt{(\cos^2 \theta - \cos^2 \varphi)}}{\cos \theta + \sqrt{(\cos^2 \theta - \cos^2 \varphi)}}. \quad . \quad . \quad (4)$$

* Rankine "On the Stability of Loose Earth," Phil. Trans., 1856–7.

† Applied Mechanics, § 112.

‡ Ibid., §§ 195–7.

when w is the heaviness of the soil, x the depth of the point of application, and θ the angle of surface slope.

The intensity of vertical pressure at the same point upon a plane parallel to the surface is obviously

$$p_x = wx \cos\theta. \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad (5)$$

When the surface has assumed a permanent slope at the angle of repose, $\theta = \varphi$ and

$$p_y = wx \cos\varphi = p_x. \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad (6)$$

When the surface is horizontal, $\theta = 0$ and

$$p_x = wx; \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad (7)$$

$$p_y = wx\frac{1 - \sin\varphi}{1 + \sin\varphi}. \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad (8)$$

Where the earth lies against a vertical plane, as the back of a retaining wall, the pressure in the direction parallel to the surface of the soil causes an effort which is equal to

$$P_y = \int_0^H p_y dx, \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad (9)$$

$$= \tfrac{1}{2}wH^2 \cos\theta \frac{\cos\theta - \sqrt{(\cos^2\theta - \cos^2\varphi)}}{\cos\theta + \sqrt{(\cos^2\theta - \cos^2\varphi)}};$$

and the point of its application is situated at a distance below the top of the wall

$$x_0 = \tfrac{2}{3}H. \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad (10)$$

When the surface of the soil lies at the natural angle of repose, $\varphi = \theta$,

$$P_y = \tfrac{1}{2}wH^2 \cos\varphi; \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad (11)$$

When the soil is level with the top of the wall, $\theta = 0$,

$$P_v = \tfrac{1}{2}wH^2\,\frac{1 - \sin\varphi}{1 + \sin\varphi}. \quad . \quad . \quad . \quad . \quad . \quad . \quad . \qquad (12)$$

This force is applied at the depth $x_0 = \tfrac{1}{3}H$, and has a moment

$$P_v x_0 = \tfrac{1}{6}wH^3\,\frac{1 - \sin\varphi}{1 + \sin\varphi}. \quad . \quad . \quad . \quad . \quad . \quad . \quad . \qquad (13)$$

The moment of the wall about the outer edge is to be divided by a suitable factor for safety to determine a value which is to be placed equal to the above:

$$\frac{1}{2a}w'Hb^2 = M\,\frac{1}{a} = P_v x_0 = \tfrac{1}{6}wH^3\,\frac{1 - \sin\varphi}{1 + \sin\varphi}; \quad . \qquad (14)$$

$$M = \frac{a}{3}wH^3\,\frac{1 - \sin\varphi}{1 + \sin\varphi}; \quad . \quad . \quad . \quad . \quad . \quad . \quad . \qquad (15)$$

$$b = H\sqrt{\frac{1 - \sin\varphi}{1 + \sin\varphi}}\sqrt{\frac{2}{3}\cdot\frac{aw}{w'}}; \quad . \quad . \quad . \qquad (16)$$

which equations apply when the overturning moment is a minimum.

Where jar or shake produces a displacement by settlement of the earth behind a retaining wall, the *maximum* possible pressure may be encountered, and we shall have

$$M = \frac{aP_v(\text{max.})\,x_0}{\tfrac{1}{2}b};$$

$$= \frac{2}{3}awH^3\,\frac{1 + \sin\varphi}{1 - \sin\varphi}; \quad . \quad . \quad . \quad . \quad . \quad . \quad . \qquad (17)$$

$$b = H\,\frac{1 + \sin\varphi}{1 - \sin\varphi}\sqrt{\frac{2}{3}\cdot\frac{aw}{w'}}. \quad . \quad . \quad . \quad . \quad . \quad . \qquad (18)$$

It is usually the safer course to assume these latter conditions, and to give structures receiving such lateral pressures the greatly enlarged dimensions and stability thus indicated.

42. **The Pressures on Retaining Walls** which sustain level embankments are due to the resultant of the pressure produced by a fluid mass of equal depth and density, and the resistance to motion produced in such a mass by the friction of its particles. The magnitude of the intensity of this resultant pressure may be obtained from the expressions given in the preceding article, or the following treatment may be adopted:

Three cases may arise:

(1) The mass may be perfectly fluid.

(2) The mass may be semi-fluid or semi-solid, and friction may act to reduce the pressure tending to cause the mass to slide or to overturn.

(3) The mass may be of the kind last described, and its internal friction may act to intensify the pressure upon the back of the wall.

The wall, when yielding, may either slide or overturn. It usually gives way by "bulging" on the face, and finally crumbles down: it thus often overturns; it rarely slides on the bed of its foundation.

The First Case is illustrated by masonry dams and by retaining-walls subject to the pressure of wet quicksand or of other soil capable of free flow.

In this case $\varphi = 0$, and $\tan \varphi = f = 0$, in the preceding equations; and the pressure at any given point, situated at a distance y beneath the surface level is of equal intensity in all directions, and is

$$p = wy, \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad (1)$$

in which w is the weight of the unit of volume of the mass. It is a maximum at the bottom, where p max. $= wH$.

The total pressure on the unit length of a vertical wall is the mean pressure, from top to bottom, multiplied by the height H; i.e.,

$$P = w \int_0^H ydy = \tfrac{1}{2}wH^2. \quad . \quad . \quad . \quad . \quad . \quad (2)$$

This is the pressure tending to cause the wall to slide. If the friction of the wall on its bed is less, i.e., if

$$F = fW < P,$$

the wall will fail. If

$$F = fW > P, \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad (3)$$

the condition of stability in this respect is complied with, and the wall will stand. For security, we should have

$$F = afW. \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad (4)$$

The point of application of this sliding effort, P, is determined by ascertaining the mean lever-arm of all the elementary efforts tending to overthrow the wall. Thus, the moment of any elementary force, pdy, about the base, calling y the depth from that point to the bottom, and taking unity of length, is

$$m = pydy; \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad (5)$$

and the total moment is

$$M = \int_0^H pydy;$$

$$= w\int_0^H (H-y)ydy = \tfrac{1}{6}wH^3. \quad . \quad . \quad . \quad (6)$$

This quantity being less, or greater, than the moment of resistance of the wall, i.e.,

$$\tfrac{1}{2}Wt \gtrless \tfrac{1}{6}wH^3, \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad (7)$$

t being the thickness of the wall, the wall will stand or fall accordingly.

Adopting for the factor of safety, a, any desired value, the equation becomes

$$\tfrac{1}{2}Wt = \tfrac{1}{6}awH^3; \qquad t = \tfrac{1}{3}\frac{awH^3}{W}; \quad . \quad . \quad . \quad (8)$$

which gives the required thickness of wall.

The point of application of the resultant pressure on the wall, measured from the bottom, is evidently to be found by dividing M by P; i.e.,

$$\bar{y} = \frac{M}{P} = \tfrac{1}{3}H. \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad (9)$$

The "Centre of Pressure" is the point of application of the resultant force, P, and is that point at which, if a force equal and opposite to P be applied, it would produce an equilibrium of efforts and of moments. Its position is measured from the surface, as above, and the depth of the centre of pressure is equal to the quotient of the moment of inertia of the surface divided by its statical moment, which latter is equal to its area multiplied by the depth of its centre of gravity.

The total pressure on the surface is thus equal to the weight of a column of the fluid having that surface as a base, and a height equal to the depth of the centre of gravity of this area below the surface of the fluid.

The Second Case is met with when a mass of earth piled against a wall, or an embankment sustained by a retaining-wall, settles against the back of the wall without jar or other action tending to increase pressure. In this case the pressure is less than that produced by a fluid mass of equal density, and is the less as the friction and adhesion of the soil are greater. The friction and adhesion attaining a certain limit, the soil stands without support; or, passing this limit, it may even require the exertion of a force to throw down a vertical face.

To determine the pressure on the back of a vertical wall, under the assumed conditions, we may use the equations already given, or let the angle $PBG = \varphi$ represent the angle

of repose, or the angle at which the soil will lie undisturbed by gravity. Assume a plane, BE, along which motion may take place should the wall yield; let its angle with the horizontal be called θ, and let its angle with BP be β.

As the angle β increases from zero to $90° - \varphi$, the tendency to slide increases from zero to a maximum; but the weight of the mass sliding, CBE, decreases from a maximum

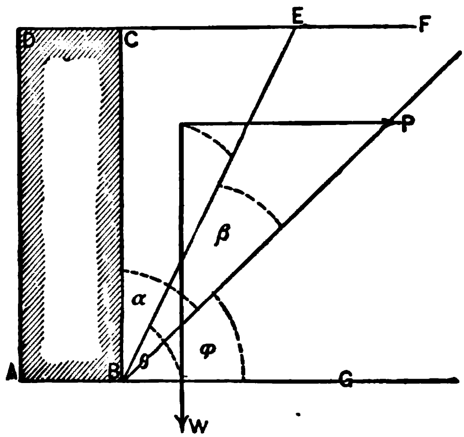

FIG. 19.—RETAINING WALL.

to zero. The pressure on the back of the wall is thus zero for either $\beta = 90° - \varphi$, or $\beta = 0$, and is a maximum at an intermediate value of β.

Let W be the weight of the mass sliding, CBE, and P the reaction of the wall, or its equal quantity, the pressure on the wall. An equilibrium evidently exists between these two forces, the pressure, P', on the surface BE, and the force of friction. Resolving perpendicularly and parallel to that surface, since $CBE = 90 - \theta$,

$$W \cos\theta + P \sin\theta - P' = 0; \quad . \quad . \quad . \quad . \quad (1)$$

$$W \sin\theta - P \cos\theta - fP' = 0; \quad . \quad . \quad . \quad . \quad (2)$$

$$W(\sin\theta - f \cos\theta) - P(\cos\theta + f \sin\theta) = 0;$$

and $$P = W\frac{\sin\theta - f\cos\theta}{\cos\theta + f\sin\theta}$$

$$= W\frac{\sin\theta - \cos\theta\tan\varphi}{\cos\theta + \sin\theta\tan\varphi}; \quad . \quad . \quad . \quad . \quad . \quad . \quad (3)$$

$$= W\frac{\tan\theta - \tan\varphi}{1 + \tan\theta\tan\varphi};$$

$$= W\frac{\tan\theta - f}{1 + f\tan\theta}. \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad (4)$$

But $$W = \tfrac{1}{2}wH^2\operatorname{cotan}\theta = \tfrac{1}{2}wH^2\frac{\cos\theta}{\sin\theta};$$

and hence, $$P = \tfrac{1}{2}wH^2\frac{1 - f\cot\theta}{1 + f\tan\theta};$$

$$= \tfrac{1}{2}wH^2\frac{1 - \cot\theta\tan\varphi}{1 + \tan\theta\tan\varphi}; \quad . \quad . \quad . \quad . \quad . \quad . \quad (5)$$

which becomes zero when $\theta = \varphi$, and when $\theta = 90°$, as already indicated, passing through an intermediate value at which P becomes a maximum; thus, when $\theta = \frac{1}{2}(90° - \varphi)$,

$$\tfrac{1}{2}wH^2\tan^2\tfrac{1}{2}(90° - \varphi) = P = \tfrac{1}{2}wH^2\frac{1 - \sin\varphi}{1 + \sin\varphi}. \quad . \quad (6)$$

The moment of P about the lower edge of the wall is

$$M = \tfrac{1}{3}P.H = \tfrac{1}{6}wH^3\frac{1 - \sin\varphi}{1 + \sin\varphi}. \quad . \quad (7)$$

The moment of the wall resisting rotation is, if t be its thickness and w' the "heaviness" of the masonry,

$$M' = \tfrac{1}{2}w'Ht^2. \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad (8)$$

These moments should be equal for equilibrium, but a factor of safety of at least 4 should be adopted. Then we have $M' = 4M$, and if the factor of safety is a,

$$t = H\sqrt{\frac{a}{3}\cdot\frac{w}{w'}\cdot\frac{1 - \sin\varphi}{1 + \sin\varphi}}; \quad . \quad . \quad . \quad . \quad . \quad . \quad (9)$$

or, if $a = 4$,

$$t = 2H\sqrt{\frac{1}{3}\,\frac{w}{w'}\,\frac{1-\sin\varphi}{1+\sin\varphi}}. \quad \ldots\ldots \quad (10)$$

Values of the functions of φ are given in Chapter VI.

The Third Case is illustrated by retaining-walls on which the pressure is intensified by jar or change of volume due to alternate freezing and thawing, the action of friction tending to retain the maximum pressure, and by foundations.

Foundations, whether of structures or of machinery, resting upon soil, depend for their permanence and stability upon the friction of the particles composing it. The pressure upon the bed of the foundation causes a tendency in the earth below to slide laterally, and thus to permit the foundation and superincumbent structure to descend. The liability to slide is zero where the material is rigid, and becomes greater as the friction and cohesion of the soil decrease; until, in freely-flowing soils, like quicksand and mud, the sole supporting pressure is that due the hydrostatic head measured from the surface to the given level, and is proportional to the density of the material.

The maximum horizontal pressure resisting this sliding is, since the direction of friction-resistance is here reversed, and we have $+f\sin\varphi$ in place of $-f\sin\varphi$, and the reverse,

$$p \text{ max.} = wh\frac{1+\sin\varphi}{1-\sin\varphi};$$

and the greatest pressure vertically is

$$p' \text{ max.} = p \text{ max.}\frac{1+\sin\varphi}{1-\sin\varphi} = wh\left(\frac{1+\sin\varphi}{1-\sin\varphi}\right)^2;$$

which pressure is that which would barely sustain the load on the foundation or would resist the thrust of earth, as described at the beginning of this article. If the factor of safety is taken as a, the pressure on the lower surface of a foundation is readily obtained as below.

The supporting power of a foundation, and the resistance of a retaining-wall subject to jar or to the action of frost, is

evidently always limited by the *maximum* value of p_y for the given case, which is

$$p_y = wy\frac{1 + \sin\varphi}{1 - \sin\varphi};$$

the corresponding vertical pressure thus cannot exceed

$$p' = p_y\frac{1 + \sin\varphi}{1 - \sin\varphi} = wy\left(\frac{1 + \sin\varphi}{1 - \sin\varphi}\right)^2;$$

and the total weight which can be sustained is

$$p'A = Awy\left(\frac{1 + \sin\varphi}{1 - \sin\varphi}\right)^2;$$

and the limit allowable for the ratio by which the weight of the structure exceeds the weight of the displaced soil is, at the point of maximum load,

$$m = \frac{p'}{wy} = \left(\frac{1 + \sin\varphi}{1 - \sin\varphi}\right)^2. \quad . \quad . \quad . \quad . \quad . \quad (11)$$

The total horizontal resistance is, at the side of the foundation, the same as on a retaining-wall exposed to jar,

$$P_y = \frac{1}{2}wy^2\frac{1 + \sin\varphi}{1 - \sin\varphi}, \quad . \quad . \quad . \quad . \quad . \quad . \quad (12)$$

acting at $$y_c = \frac{1}{3}y_0, \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad (13)$$

below the surface, when y_0 measures the total depth of foundation-wall below the top level.

Taking a as a factor of safety, the pressure on the lower surface of a foundation of the area A, carrying a load W, may be such that

$$\frac{W}{A} = p' \text{ max.} = awh\left(\frac{1 + \sin\varphi}{1 - \sin\varphi}\right)^2; \quad . \quad . \quad . \quad (14)$$

and the area and the total weight should be

$$A = \frac{W}{awh} \div \left(\frac{1 + \sin\varphi}{1 - \sin\varphi}\right)^2;$$

$$W = aA\,Wh\left(\frac{1 + \sin\varphi}{1 - \sin\varphi}\right)^2; \quad . \quad . \quad . \quad . \quad . \quad . \quad (15)$$

the weight of building, if uniformly distributed, exceeding the weight of soil displaced by its underground masonry in the proportion

$$r = \left(\frac{1 + \sin\varphi}{1 - \sin\varphi}\right)^2.$$

Thus, for $f = \tan\varphi = \tan 15^\circ = 0.27$, this value is $r = 2.9$; for $\varphi = 30^\circ, f = 0.58, r = 9$; and for $\varphi = 45^\circ, f = 1, r = 34$, nearly, the value of r and the stability of the foundation increasing with great rapidity as f assumes large values. Where jar occurs, the factor of safety must be very large, since this causes a direct tendency to relieve pressure, to reduce friction, and to cause to bow.

Values of f, and of the more important of the factors above, will be given in Chapter VI. as derived by experiment.

43. **The Friction of Fluids,** having its origin in conditions essentially different from those met with in the motion of solids in contact, is subject to quite different laws. When a fluid moves in contact with a solid, or when it flows in a current through a mass of fluid, precisely the same conditions arise. In either case, the resistance experienced is due to the relative motion of layers of fluid moving in contact with each other.

At surfaces of contact with a solid, the fluid lies against the solid without appreciable motion; as the distance from the surface of layer after layer is increased, the relative velocity of the fluid and the solid becomes greater up to a maximum, which is reached at the farthest point in the mass of fluid from the two bounding surfaces. This process can be readily ob-

served by watching the behavior of the fine threads of marine vegetation often covering the sides of a ship below the water-line, while the vessel starts slowly into motion in still water. Fluid friction is, therefore, the friction of adjacent bodies of fluid in relative motion, and is due to the formation of small whirls or of large eddies in the two bodies, the production of which absorbs energy from the flowing mass. The friction of the fluid finally extinguishes this energy of eddy-motion, converting it into heat, and raising the temperature of the mass by the introduction of the heat-equivalent of the mechanical energy thus destroyed. The resisting property which thus effects this conversion, and which is the cause of fluid-friction, is called viscosity. No true friction, in the sense in which that term is commonly used, has been recognized in fluids. The best evidence that it does not exist is, perhaps, the fact that the friction of fluids is unaffected by variation of pressure.

44. **The Laws of Fluid Friction** are tolerably well established. They are, for all fluids, whether liquid or gaseous:

(1) Fluid Friction is independent of the pressure between the masses in contact.

(2) The Resistance of Fluids is directly proportional to the area of the surface exhibiting it.

(3) This resistance is proportional to the square of the relative velocity at moderate and high speeds, and to the velocity nearly at very low speeds.

(4) It is independent of the nature of the surfaces of the solid against which the stream may flow; but it is dependent to some extent upon the degree of roughness of those surfaces.

(5) It is proportional to the density of the fluid, and is related in some way to its viscosity.

The resistance to relative motion, in cases of fluid friction, against solids, in ordinary work, may be expressed by

$$R = fAV^2, \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad (1)$$

calling f the resistance on an area unity, A the area of the surface exposed, and V the velocity of gliding of the fluid over

it. The relation of the total resistance to the head producing flow, $h = \frac{V^2}{2g}$, is given by

$$R = f'wA\frac{V^2}{2g}; \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad (2)$$

in which $$f' = \frac{2gf}{w},$$

and w is the "heaviness" of the fluid, i.e., its weight per unit of volume.

The work of friction is

$$U = Rs = RVt = fAV^2t;$$

$$= f'Awt\frac{V^2}{2g}. \quad . \quad . \quad . \quad (3)$$

The quantities f and f' are sometimes distinguished by calling f the resistance per unit of area of surface, and f' the coefficient of fluid friction. As stated already, these values are not absolutely constant with varying velocities, but must be modified often to meet special cases. Thus, Eytelwein takes

$$f = a + \frac{b}{V}; \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad (4)$$

Weisbach takes

$$f = a + \frac{b}{\sqrt{V}}. \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad (5)$$

Values of f and of f' will be found in Chapter VI.

They range from $f = 0.0026$ to $f = 0.005$ and from $f' = 0.0025$ to $f' = 0.0049$.

45. Viscosity and Density, while they do not affect to any observable extent the rate of flow of fluids retarded by friction, and do not usually affect the values of the coefficient, do nevertheless determine the total expenditure of energy in the production of the flow of a given volume at a given velocity. The fact that the coefficients used for the limpid liquids, as

water, the vapors, as steam, and the gases, as air, and at all pressures, are in practice sometimes taken without serious error as the same, indicates that this resistance is in such cases a kinetic form of resistance rather than one due to intramolecular action.

Viscous fluids, as heavy oils, molasses, tar, and viscous solids, as ice or the resins, follow laws which have not been fully ascertained; but their flow is evidently greatly influenced by their molecular constitution.

46. **Molecular or Internal Friction** is well known to exist in solids which can be made to flow. It is a form of friction frequently observed, but not as yet fully investigated, and is still but little understood.

One of the best illustrations is that described by Professor William Thomson. A copper wire was stretched by an intermittently increasing load, and the successive elongations noted. The load was then removed by a similar process, and the successive decrements of length were also observed. It was found that the latter were not precisely equal to the former, although the wire finally regained the original length; but that there seemed to have come into play some force resisting motion both ways, as does friction.

It is also found that molecular displacements, once taking place in the action of externally originating forces, sometimes give rise to a less resistance when the operation is repeated: just as if an originally present frictional resistance had been partly overcome by the smoothing of the molecular path, reducing resistance as frictional resistance to sliding or rolling is reduced by repeated sliding or rolling on the same track. An illustration of this phenomenon is seen in the fact that a magnet thoroughly demagnetized is remagnetized more easily with the original polarity than in the opposite direction.

A modification of this action is evidently operative in viscous solids; and it is probable that it is also seen in the behavior of the viscous liquids while changing form and while flowing in currents.

47. **The Compound Friction of Lubricated Surfaces,** as it may be termed, or friction due to the action of surfaces

of solids partly separated by a fluid, is observed in all cases in which the rubbing surfaces are lubricated. In such instances the solids are usually not completely separated by the liquid film interposed between them, but partly rub on each other, and are partly supported by the layer of lubricant which is retained in place by adhesion and by capillary action. The rubbing together of the two solids produces wear, the amount of which is indicated by the rate at which the lubricant becomes discolored and charged with abraded metal. The work of friction, both of solid and of liquid, is transformed into heat, and is disposed of as the bearing heats, principally by radiation and conduction to adjacent parts, and partly by the flow of the lubricant. In all cases some abrasion is indicated by the change produced in the lubricant, and some heating is usually perceived in the bearing.

With very heavy pressures and slow speeds, the journal and bearing are forced into close contact, as is shown by their worn and often abraded wearing surfaces; while with very light pressures and high velocities the journal floats on the film of fluid which is continually interposed between it and the bearing. In this case the friction occurs between two fluid layers, one moving with each surface. There are thus evidently two limiting cases between which all examples of satisfactorily lubricated surfaces fall: the one limit is that of purely solid friction, which limit being passed, and sometimes before, abrasion ensues; the other limit is that at which the resistance is entirely that due to the friction of the film of fluid which separates the surfaces of the solids completely.

The laws governing the friction of lubricated surfaces are evidently neither those of solid friction nor those of fluid friction, but will approximate to the one or the other as the limits just described are approached. As will be seen later, the value of the coefficient of friction varies with every change of velocity, of pressure, and of temperature, as well as with change of character of the surfaces in contact.

The laws of complex friction are considered at great length in the last chapter.

Where mixed friction is met with, it will usually be found

that its laws approximate to those of solid friction as the journal is run dry, and to those of fluid friction as it is flooded with oil. Thus a journal or bearing surface fed with oil by an oil-cup, and where no oil-grooves are used to distribute the oil, will exhibit a total friction in some cases nearly proportional to the total pressure, the latter being varied; while similar surfaces flooded with oil, as by the oil-bath, offer a resistance sometimes nearly independent of the pressure, and but little, if appreciably any, greater with heavy than with light loads. A *perfectly* lubricated bearing should follow the laws of fluid friction, and its friction should be independent of the intensity of pressure produced by the load, varying as the square of the speed of rubbing. Such perfect lubrication has never yet been attained.

For perfect lubrication, assuming it practicable with complete separation of the surfaces, the laws of friction would become:

(1) The coefficient is inversely as the intensity of the pressure, and the resistance is independent of the pressure.

(2) The friction coefficient varies as the square of the speed.

(3) The resistance varies directly as the area of journal and bearing.

(4) The friction is reduced as temperature rises, and as the viscosity of the lubricant is thus decreased.

These laws will probably hold, even with the greases, which all become fluid when introduced between the rubbing surfaces.

It is found by experiment, as stated later, that the perfection of this form of lubrication depends upon the amount of fluid-pressure produced between the surfaces by forcing in the lubricant between them. This separation occurs to an important extent at high speed and less at low velocities. Hence, the friction of lubricated parts is often found to decrease at low speed with increase of velocity, while increasing at high speeds as velocity increases.

48. The Limits of Pressure for Lubricated Surfaces are determined by the nature of the materials composing them, and by their smoothness and exactness of fit, as well as by the speed of rubbing, the character of the lubricant, and the

methods of its application. A higher pressure is usually permissible on hard than on soft material; although when the soft materials, as for example common white alloys for bearings, are well sustained by a harder metal, the heaviest pressures allowed by the lubricant may be carried.

The more viscous the lubricating substance, and the stronger the capillary action taking it into the space between the journal and the bearing, the higher the pressure safely carried. With increase of speed the maximum pressure is lessened, and it is usual to take the intensity of pressure as inversely as the velocity of rubbing. Values of p thus determined will be given in Art. 127.

49. The Magnitude of the Waste of Energy by friction is measured in horse-power by the expressions (British measure),

$$(1)\ \text{Flat surfaces,} \qquad HP = \frac{fPV}{33{,}000};$$

$$(2)\ \text{Cylindrical surfaces,}\ HP = \frac{fPRd}{127{,}000};$$

when f, P, and V are the coefficient of friction, the load and the speed of rubbing in feet, and R and d are the revolutions per minute and diameter of journal in inches.

The Methods of Reducing Waste of Energy by friction in mechanism are based upon very simple principles. It is evident that to make the work and power so lost a minimum it is necessary to adopt the following precautions:

(1) Make the coefficient of friction the least by proper choice of rubbing surfaces and by the best lubrication. To do this we should have at least one of the rubbing surfaces of a granular metal, and if possible both—that one which it is easier to replace being of the softer metal. The surfaces should not be subjected to a normal pressure beyond which the lubricating matter will be expelled. For slides, a much less pressure should be taken than for journals, as they have not as free a lubrication as well-arranged cylindrical journals;

but this limit is best determined by reference to the speed of rubbing and the nature of the lubricant.

(2) Make the space through which the friction is to act a minimum by reducing the diameters of all journals to the least compatible with safety under the stresses they are expected to sustain. The work done is independent of the length of the journal, except as it may modify pressures, and thus the coefficient of friction.

(3) Properly fitting the bearing surfaces, removing that portion of the bearing near the jaws; and transferring the bearing surface to the bottom, one sixth of the circumference of the journal may be thus removed. A journal well fitted cold is not necessarily a good fit after it becomes heated by friction, owing partly to the want of homogeneousness of the metal of the journal and bearing; a worn journal has less friction than when new. It is a question whether all journals should not be brought to a proper bearing and given a high polish before they are considered fit to perform their office. It is now usual carefully to grind all cylindrical journals, and to secure a very perfect fit in the bearing before setting the machinery at work.

(4) Giving the journals such forms and such size as will allow them to convey away the heat generated, either by radiation from their surfaces or by conduction through the mass of metal, to circulating water, to lubricating matter, or to adjacent masses.

(5) Securing an efficient system of supply of the lubricant.

CHAPTER III.

THE LUBRICANTS.

50. **The Lubricants** are of three classes: Solids, Semi-solids, and Liquids. The first class are usually minerals, as graphite and steatite; the second class is principally composed of the animal fats, but includes also some of the vegetable greases and special preparations from mineral oils. In the third class are included a very great variety of oils derived from all of the three great kingdoms of nature.

The Natural Fats and Oils constitute a large and well-defined group of organic compositions, having some analogy chemically to the compound ethers. Hydrocarbons constitute the principal and characteristic portion of each of these compounds, and as a rule the higher their proportion and the less the oxygen the higher the temperatures of fusion. The presence of albuminoids in animal and vegetable fats and oils causes a tendency to a decomposition, resulting in the production of "rancidity." When thoroughly purified by the removal of the mucilaginous and albuminous portion, rancidity does not occur. These fats and oils are composed of stearine, margarine, and oleine in varying proportions; the former are solid, the latter is liquid at common temperatures, and the proportion in which these constituents are found in any fatty substance determines its temperature of solidification or of fusion.

The mineral oils and greases are originally derived from vegetable matter, but are so completely altered as to constitute a distinct class. They contain no oxygen when first obtained from the earth, and absorb it from the atmosphere but slowly and in usually insignificant amount.

51. **The Valuable Qualities of Lubricants** determine their power of reducing friction and their endurance, as

well as that of the surfaces on which they are used. The amount of frictional resistance to the motion of machinery is obviously determined by the character of the lubricating material. Nearly all recent experiments in this field have been made in investigations of the value of lubricants which include very much more than a single measure of the coefficient of friction. The later determinations of the friction of lubricated surfaces at the various pressures and speeds which are commonly met with in modern machinery will therefore be given after discussing the nature of lubricating materials, and the standard or other methods of ascertaining their value. The tables to be given later will serve the mechanic, the engineer, or the designer of machinery as data by means of which to estimate the probable losses of power by friction under every usual set of conditions met with in practice.

The value of a lubricant, as a lubricant, is nearly independent of the market price. Some of those materials which would be most useful in reducing friction, could they be so applied, are, however, entirely unknown to consumers of lubricating substances, because of their monopoly for other purposes, for which they are in such demand as to entirely remove them from a market in which other unguents can be obtained at comparatively low price. The best known lubricant for general purposes—sperm-oil—is far less used than the less excellent but cheaper lard oil, which in turn is less generally used than the mineral and mixed oils with which the market is always largely supplied.

The effect of friction—rolling as well as sliding—is to wear and abrade solids, and with fluids as well as with solids, to generate heat to an amount which is the exact equivalent of the work of friction, and which, could it be all collected and measured, would be found to be a precise measure of the power wasted and lost in consequence of the friction. The amount of heat thus produced is equal to one British "thermal unit" * for each 772 foot-pounds of work expended in overcoming friction. This figure is that known as Joule's "mechanical equiva-

* A British thermal unit is the quantity of heat required to raise the temperature of a pound of water one degree Fahrenheit.

lent of heat." Where the work is measured by the metric system this corresponds to the development of one "*calorie*" * of heat for each 424 kilogramme-metres of work done in overcoming frictional resistance.

This evolution of heat has a serious ill effect in several ways: it reduces the viscosity of lubricants, thus rendering them more liable to exude from between the rubbing surfaces at high pressures; it is cumulative, and causes danger to become more and more imminent as it progresses beyond the limit within which conduction and radiation may dispose of it to surrounding objects as fast as generated; it causes serious injury to the surfaces in contact, cracking, distorting, and abrading them, and thus increasing the friction while destroying journals and bearings; it often even ignites the lubricant, overheating, softening, and weakening the abrading metals and endangering all combustible material in its neighborhood. The journals of machinery are often actually welded into their bearings. The burning of mills and of steam-vessels, and the breakage of car-axles, and consequent destruction of trains loaded with passengers, sometimes result from the use of improper lubricants or of badly proportioned rubbing parts.

Since lubrication has for its objects both the reduction of friction and the prevention of excessive development of heat, the engineer resorts to the expedient of interposing between the rubbing surfaces a substance having the lowest possible coefficient of friction and the greatest capacity for preventing or reducing the development of heat. It is evident, then, that in order that any substance may be efficient as a lubricating material it must possess the following characteristics:

(1) Enough "body" or combined capillarity and viscosity to keep the surfaces between which it is interposed from coming in contact under maximum pressure.

(2) The greatest fluidity consistent with the preceding requirements, i.e., the least fluid-friction allowable.

(3) The lowest possible coefficient of friction under the

* The metric "*calorie*" is the heat required to raise the temperature of a kilogramme of water one degree Centigrade.

conditions of actual use, i.e., the sum of the two components, solid and fluid friction, should be a minimum.

(4) A maximum capacity for receiving, transmitting, storing, and carrying away heat.

(5) Freedom from tendency to decompose or to change in composition by gumming or otherwise, on exposure to the air or while in use.

(6) Entire absence of acid or other properties liable to produce injury of materials or metals with which they may be brought in contact.

(7) A high temperature of vaporization and of decomposition, and a low temperature of solidification.

(8) Special adaptation to the conditions, as to speed and pressure of rubbing surfaces, under which the unguent is to be used.

(9) It must be free from grit and from all foreign matter.

Oils must be used with some caution when applied to journals upon which other lubricants have been employed. It sometimes happens that two oils are entirely incapable of working together, and this incompatibility may cause trouble when they are used together, or even successively. A minor good quality possessed by some lubricants in greater degree than others is that of being readily removed, and allowing the bearing surfaces to be easily cleansed when they have become soiled and gummed by alteration of the unguent, and by the gathering of dust and abraded metal upon them.

Oils should not be liable to decomposition by heat or wear, or to separation when mixed, either in use or by long standing, or by alteration of temperature. They should, if mixed, always have the same specified composition. Uniformity in this respect is as important as excellence of quality of the normal mixture, and the quality of the oil is usually of more importance than the quantity. The adhesiveness of the oil to the metal, and the ease of flow, with minimum fluid-friction, are the essential characteristics of a good combination of materials in bearings and lubricant. Cast-iron is somewhat spongy in texture, and is therefore an exceptionally good metal for bearing surfaces, when of ample area; a dense,

smooth-surfaced metal is more subject to friction than the same surface finely scratched or slightly roughened. Surfaces may be *too* smooth.* The best mineral oils are often better in the above-mentioned qualities than the organic oils; and sperm, neat's-foot, and lard, for ordinary work, follow in order. The heavy petroleums are usually best for heated surfaces, as in steam cylinders, and often for heavy work on cool journals; although many engineers still prefer the better class of greases, or even sperm-oil.

The value of a lubricant to the consumer, as is seen from what has been just stated, depends on its cost in the market, its efficiency in reducing friction, its durability under wear, its freedom from liability to "gum," its freedom from acid and from grit, and its permanence of composition and of physical condition when subjected to changes of temperature, and also, frequently, its capacity for carrying away heat from journals already heated.

Thus sperm-oil is one of the very best of known lubricants; but its high price precludes its use, except for special purposes. Other oils are cheap, but have little lubricating power; still others are good reducers of friction, but do not wear well, or cannot be retained on the journals; others, as linseed and the drying oils generally, although sometimes excellent, otherwise gum so seriously that they cannot be used for lubrication; while a good deal of the tallow in the market, and some other lubricants, contain acids of decomposition, or acids which have been used in their clarification, which have not been so completely removed as to prevent injury by their action on the metals. Some lubricants cannot be used at low temperatures because they are liable to congeal, and others cannot be used in steam cylinders, or where high temperature is liable to be met with, because they decompose or vaporize under such circumstances.

Every dealer in oils and every consumer of lubricants who desires to know with certainty whether he has in any case precisely that lubricant and that quality which is nominally

* Woodbury.

given him, must resort to some method of identification of the material. Every user of such a material who desires to know whether it is well adapted to a specific purpose, or who wishes to find out what are its peculiar characteristics, must find some method of testing it, and of thus ascertaining whether, under the conditions arising in his practice, it will serve his purpose. He must know whether it will bear the pressure, and will run without heating his journal at the speed to which he must subject it.

As will be seen hereafter (Chapter VIII.), the price of an oil is usually of little importance in comparison with its friction-reducing power. A saving of a few dollars' worth of oil at the expense of many times its value in heated and injured bearings, or in power and fuel, is extravagance.

In order that the oil should retain its good quality and value, it should be so stored as not to be liable to alteration by the action of the air and of sunlight. Lubricants which do not adhere to the rubbing surface, which are wastefully fluid, which contain acids or grit are expensive to use, even if they cost nothing in the market.

The following table shows the usual order of ordinary prices of the principal oils:

(1) Sperm Oil.
(2) Seal Oil, Olive Oil, Lard Oil — These may change places at times.
(5) Rape-seed Oil.
(6) Other Seed Oils: Cotton-seed. Linseed.
(7) Castor Oil.
(8) Fish Oils: Cod. Menhaden. Porgy.
(9) Whale Oil.
(10) Mineral Oils.
(11) Rosin Oil.

The Best Lubricants are in general the following, for usual conditions met with in practice:

Under low temperatures, as in rock-drills driven by compressed air—light mineral lubricating oils.

Under very great pressures with slow speed—graphite, soapstone, and other solid lubricants.

Under heavy pressure with slow speed—the above, and lard, tallow, and other greases.

Heavy pressures and high speed—sperm-oil, castor-oil, heavy mineral oils.

Light pressures and high speed—sperm, refined petroleums, olive, rape, cotton-seed.

Ordinary machinery—lard-oil, tallow-oil, heavy mineral oils, and the heavier vegetable oils.

Steam cylinders—heavy mineral oils, lard, tallow.

Watches and other delicate mechanism—clarified sperm, neat's-foot, porpoise, olive, and light mineral lubricating oils.

For mixture with mineral oils, sperm is best; lard is much used; cotton-seed and olive are good.

Many different conditions must, therefore, be studied, and the behavior of the lubricant determined with reference to each before it can be known, with any degree of certainty, what is its real value for any specified purpose, and it is equally evident that the conditions under which the behavior of an oil or other lubricating material is to be determined should always be those approximating with the greatest possible exactness to the conditions proposed in its actual use. An exact theory of the commercial value of lubricants will be developed in a later chapter.

52. **Lubricants**, as already seen, are sometimes solid, but usually liquid; and of the liquid unguents there are many varieties in the market, which differ in their viscosity and cohesiveness as widely as they do in nearly every other quality, and range from the most limpid watch-oils to those "heavy bodied" and densest of all the oils—castor-oil and rosin-oil. We have semi-solid lubricants, of which tallow, soap, cocoanut oil, and wax are illustrations; and still others are perfectly hard and solid, as graphite and soapstone.

The engineer also uses what are known as "anti-friction metals," one of the oldest and best known of which is the so-called "Babbitt-metal." These are permanently fixed in the bearings in the form of linings, and their peculiar use is to present to the journal, instead of the hard, unyielding, and resistant surface of the metal itself, a material which more readily and perfectly adapts itself to the form of the journal which it supports.

Lead has been introduced by Mr. Hopkins to act thus temporarily, gradually, as it wears, letting the journal down to a good bearing on the brass of the boxes.

Some anti-friction metals are used without lubricants, and are therefore themselves as truly lubricants as are plumbago and similar solid materials which are usually finely ground and interposed between rubbing surfaces.

In some cases no lubrication will suffice to keep a journal from heating, or even "cutting:" in such an event the "brasses" are sometimes made hollow, and a stream of water is made to circulate through them, thus effectually keeping them cool.

In the "*Palier-glissant*" of Girard and the "Water-bearings" of Shaw, the journal is supported upon a cushion of water which is forced into a space in the journal beneath it by a pump, and at such a pressure that the journal is perfectly "water-borne," and revolves on the liquid cushion. Shaw has applied this plan successfully in supporting vertical shafts.

The Oils are the most generally applied fluid lubricants; the most common are the better known and cheaper kinds of animal, fish, vegetable, and mineral oils: of these, sperm stands admittedly at the head of the list; lard, neat's-foot, whale, tallow, seal, and horse oils are all largely used either alone or mixed. The vegetable oils in use are olive, which is by far most generally used in other countries; cotton-seed oil in the United States, palm, rape-seed, oleine, colza, poppy, pea-nut, rosin, cocoa-nut, and castor oils* are all more or less employed in

* Linseed-oil is a good reducer of friction, but dries and "gums" too rapidly to permit its use as a lubricant.

lubrication. Of the fish-oils, porpoise, cod, and menhaden* oils, are most used. The mineral oils are of two classes: the shale-oils, obtained from certain shales; and the well-petroleums, which come from extensive oil-lakes, situated usually far beneath the surface of the earth, and which are principally obtained from oil-wells in Pennsylvania and other of the United States. Glycerine is sometimes used as a lubricant for light pressures.

Of these oils, sperm excels nearly all others in its power of reducing friction, and generally excels them in endurance. Rape-seed is in some districts now displacing olive-oil as a lubricant; but the mineral oils, pure or mixed, are rapidly taking the leading place in all markets.†

53. **The Semi-fluid Lubricants, or Soft Greases,** are usually of animal origin. The term *grease* is usually restricted to those soft fats which permeate the tissues filling the cavities of the animal system, especially about the loins and among the intestines, and which are solid or nearly so at all temperatures not greatly exceeding that of the living animal. They usually liquefy at about this temperature, some of them becoming fluid at even lower temperatures than the normal. Ignited, they burn freely, with a clear light, but with a smoky flame.

The greases are composed of stearine, margarine, and oleine, in variable proportions, and are the more fluid as the latter constituent is present in larger proportion. They are partially soluble in alcohol, and freely so in ether, in essential oils, and in other oily compositions. When fresh they are white or light yellow in color, and when old and altered chemically or by mixture, often become darkened. They are always liable to alteration, becoming rancid on exposure to air and sunlight. This occurs by the development of the fatty acids, and this change, which is readily detected by their odor and taste, renders them injurious to the machinery on which they are

* The whale is not a fish, but an animal classed among the mammals.

† Portions of this chapter and of other parts of this work are from "Friction and Lubrication," lectures by the author, published by the Railroad Gazette Publication Co., New York, 1879.

used, and especially where heated, as in the cylinders of steam-engines.

Tallow, which may be taken as the best-known example of this class of lubricating materials, is the fat of domestic animals, removed from the membrane in which it is secreted usually by melting. Its quality and properties vary somewhat with the animal, and with its age and other characteristics. It is solid at common temperatures, white or nearly white, slightly odorous, and readily saponifiable. The best is obtained from mature animals, and usually, according to Chateau and other authorities, from males of the domestic animals. The greater part of the tallow of commerce is beef tallow and mutton tallow.

The greases are sometimes used in the natural state, and often mixed with other classes of lubricant.

Vaseline, and other similar preparations of mineral origin, are to be classed with the greases, as are a number of vegetable waxes and butters, as the so-called cocoa-nut oil. These are rarely used in the lubrication of mechanism, however, although the former class occasionally and the latter more frequently are introduced into mixtures.

Vaseline and the other mineral greases are obtained by the distillation of petroleum at low temperature in vacuo. The vegetable greases are usually natural products.

54. **For Hard Greases,** as for use on railways, mixtures of tallow and palm-oil with water rendered alkaline with soda are often used. Two parts paraffine, one of lard, and three of lime-water is a good grease for heavy, slow-moving journals.

A mixture of eight parts of bayberry-wax with one of graphite is very good also, and is said by a U. S. Ordnance Board to be the best-known preparation for rifle-bullets.

Grease is usually employed in lubricating axle-journals in Great Britain, and is generally of palm-oil. The following are said to be good compositions* for that climate:

* W R. Browne, *Railroad Gazette*, August 9, 1875

RAILROAD AXLE GREASE.

	For Summer.	For Winter.
Tallow	504 lbs.	420 lbs.
Palm Oil	280 "	280 "
Sperm Oil	22 "	35 "
Caustic Soda	120 "	126 "
Water	1,370 "	1,524 "

On German railroads the following composition is used:

	Parts.
Tallow	24.60
Palm Oil	9.80
Rape-seed Oil	1.10
Soda	5.20
Water	59.30
	100.00

The following is Austrian:

	Tallow.	Olive Oil.	Old Grease.
For Winter	100	20	13
For Spring and Autumn	100	10	10
For Summer	100	1	10

Tallow and "black-lead," or plumbago, "white-lead" and oil, and mixtures containing sulphur are often used as semi-fluid lubricants.

There exists a decided tendency to displace the more fluid by the less fluid lubricants, to use tallow in place of the oils, and to adopt manufactured hard greases where the more free flowing materials have been formerly generally employed. The change leads almost always, if not invariably, to loss of power by increased friction—a loss which is seldom noted—while saving in cost of lubricant by reduction of quantity used. In many cases this is not economy, and a careful determination and balancing of gains and losses is advisable before a final choice is made.

The greases have advantages over the oils other than mere reduction of cost of lubricating material. The cost of the time demanded for the supply of the lubricant is usually less with the greases; the drip is less, and the injury by soiling

floors and goods is correspondingly reduced; danger of fire is also less, and the journals will usually work more uniformly cool. The greater the consistency of the lubricant, other things being equal, the greater its endurance and economy. The number of these greases in use is very great, and their differences of value are sufficient to make their careful selection by test a matter of serious importance. The method of application is even a more important matter than the kind of lubricant, or the conditions affecting it.

55. **The Solid Lubricants** are sometimes found to work well when no fluid will answer at all. Some of them sustain immense pressures without injury. Those in general use are certain metallic compositions, mixtures of metallic with non-metallic elements—graphite, sulphur, soapstone, asbestos, lampblack, and white-lead (carbonate of lead). In some cases they are permanently and solidly fixed, and sometimes are applied at intervals between the rubbing surfaces, as are the oils.

Plumbago, or Graphite, and Soapstone are lubricants. The former is a solid form of carbon, supposed to be the ultimate product of the destructive distillation of the vegetable matter of the forests of the carboniferous or, usually, earlier periods. It is often distinctly crystalline, has a specific gravity of 1.8, and is moderately hard. Very pure graphite, containing 99 per cent. carbon, is found at Ticonderoga, N. Y.; in Cumberland, Great Britain; and in the island of Ceylon. Crude and impure graphite occurs in many other localities Very fine graphite also comes from Siberia, supplying the demand for the best grades of pencils. It is principally used for crucibles and in pencils, but is an excellent lubricating material for heavy work, and is also often found very useful for light machinery; it is used for silk-looms making delicate fabrics which would be destroyed by oil. Its value as a lubricant is sometimes greatly impaired by impurities, and especially if they are earthy and gritty. Freedom from such impurities is essential to the successful use of plumbago, either alone or mixed with other unguents.

Graphite was mentioned by Rennie in 1829: he states that "in all cases where plumbago was used it lessened friction."

General Morin, experimenting with it later, concluded that it could be used to advantage where heavy pressures were to be sustained. The author has found graphite, and graphite mixed with certain oils, well adapted for use under both light and heavy pressures. It is especially valuable to prevent abrasion and "cutting," under very heavy loads and at low velocities. Plumbago is used generally by interposition, although often forming, as just stated, an ingredient in the composition of mixed oils and of anti-friction and "anti-attrition" compounds of the first class. It should always be absolutely pure and free from grit, and should be ground to the condition of a flaky powder.

Mr. T. Shaw found it superior to oil for the tables of heavy planers.

Soapstone is a hydrated silicate of magnesia, known also as talc and as steatite. It is very widely distributed. It is soft, easily cut by the knife, and has an unctuous quality, to which it owes its name. For use as a lubricant, it must be free from gritty impurities, and can be then employed like graphite. It is extensively used in the manufacture of "packing" for the piston-rods and valve-stems of steam-machinery.

Some engineers express a preference for *soapstone* powder as a lubricant for the axles of machines. For this purpose it is first reduced to a very fine powder, then washed to remove all gritty particles, then steeped for a short period in dilute muriatic acid, in which it is stirred until all particles of iron which it contains are dissolved. The powder is then washed in pure water again to remove all traces of acid; after which it is dried, and forms the purified steatite powder used for lubrication. It is not generally used alone, but is mixed with oils and fats, in the proportion of about 35 per cent. of the powder added to paraffine, rape, or other oil; the powder may be mixed with any of the soapy compounds employed in the lubrication of heavy machinery. These solid lubricants are both used in making up packing for steam-engines, etc.

Plumbago and soapstone are both used, mixed with soap, on heavy work, and especially on surfaces of wood working against either iron or wood.

Asbestos is a silicate of lime and magnesia, having some resemblance to soapstone in its physical properties, but distinguished by its structure, occurring in, often, long silky fibres. It is spun into threads and ropes, and woven into cloth, and even felted, and made into paper. It is used for piston-rod packing and if well purified is excellent for this purpose.

Sulphur, "*White Lead*," and some other solids are used generally mixed with oils; but they are not important members of the class of substances here considered.

Woods, as lignum-vitæ, beech, hickory, oak, maple, elm, canewood, snakewood, are sometimes used as bearing surfaces, and are almost always kept cool and prevented from wearing seriously by flooding them with water. The best of these woods are, like lignum-vitæ, hard and tough in structure; they are usually obtained from the tropics.

56. **The "Animal Oils"** are usually derived from the fats of the mammiferous animals, including the whales and their relatives; but they are sometimes obtained from fish, as from the "menhaden" or "moss-bunker." The principal of these oils are sperm and whale oils, lard and neat's-foot oils. Tallow-oil is also used to some extent. They are generally obtained by melting them out from the animal tissues in which they are originally found, and by passing them through various purifying processes. All have characteristic and persistent odors, which are often, as in the case of the fish-oils, disagreeably powerful, and which are even perceived in the soaps made from them. The liquid animal oils are principally derived from the sperm and the "right" whales.

57. **Sperm Oil,** or spermaceti-oil, is the best known, and for general purposes the most excellent, of all the lubricants. It contains, according to Brande: carbon, 78; hydrogen, 11.8; oxygen, 10.2. It is found in a large cavity in the head of the sperm-whale, mingled with the solid fat, spermaceti, from which it is separated by crystallization and pressure, without heating. It is saponifiable with potash, but with difficulty, and is one of the most permanent and most valuable of all the oils. Its specific gravity ranges from 0.880 to 0.896, averaging

about 0.885. Crude "head-oil" from the cask runs about 0.88. It is the lightest of all the lubricants. Sperm-oil is of light-orange color in large masses, lighter in small quantities, transparent, has a slight fishy odor, and precipitates needle-like crystals of spermaceti at 47° F. (8.3° C.). It is solidified by nitric acid.

Used as a lubricant, it is liable to sudden fluctuations of its coefficient of friction in consequence of its changes of density and fluidity, as the spermaceti contained in it alters with varying temperature. In lubricating quality, for light work, as for spindles, it is only excelled by the very finest of the refined mineral oils, and excels nearly all other oils under heavy pressures, although often closely approached by fine petroleums. Exposed to the air it absorbs oxygen, becomes gradually "gummed" or resinous, and loses quality seriously. At 140° F. (60° C.) it gains two or three per cent. in weight in twelve hours. It has a "flashing point" at about 500° F. (260° C.).

Whale Oil is obtained from the "blubber" of the whale by removing it from the animal in great strips, which are then heated to melt the oil out from the tissues enclosing it. All the whales, including not only the varieties classed with the sperm and the right whale, but also the blackfish and their relatives, the dolphins, furnish this "train-oil." Three varieties of oil—the so-called white, yellow, and black—are brought into the market, and are mixed to form the oil of commerce. Common whale-oil is brownish yellow, transparent, disagreeably odorous, limpid at ordinary temperatures, solidifying at the freezing-point, and precipitating at times more or less spermaceti. Its density is about 0.93 at 70° F. (21° C.). It is much used in making crude soaps and for illuminating purposes, usually mixed with vegetable oils, and little used for lubrication.

58. **Lard Oil** is the most extensively used of all the animal oils, and is an excellent lubricant, although inferior to sperm-oil. It is obtained from the fats of the hog. It is exported from the United States to Europe in large quantities for the purpose of adulterating olive-oil. It is itself often adulterated

with cotton-seed oil, which latter is also used as a salad-oil, but sold, however, as olive-oil. All three oils are good lubricants. Lard from which the oil is expressed yields 62 per cent. of its weight, the specific gravity approximating 0.925. It saponifies readily, congeals at the freezing-point of water, and "flashes" under fire-test at about 500° F. (260° C.). If sperm-oil be rated at unity as a lubricant under ordinary conditions, lard-oil will stand at 0.75 to 0.95. This oil is twice as viscous as sperm. Exposed to air it absorbs oxygen with far less rapidity than sperm-oil.

59. **Neat's-foot Oil** is one of the best of lubricants, and has extensive use in the arts. It is obtained by boiling the feet, and often other parts, of cattle, and skimming off the oil which rises to the surface of the water. It has a very slight straw-yellow color, which darkens with age; it is odorless when fresh, has a pleasant taste, is limpid at all common temperatures, but congeals at about the freezing-point of water. Its density at 60° F. (15.5° C.) is 0.916. It is very frequently adulterated with other less expensive oils. When allowed to stand for any length of time, it often deposits white flakes of solid fats. Its low temperature of congelation makes it a very useful oil for out-of-door machinery. It resembles lard-oil in general appearance and qualities.

Tallow Oil is made from the tallow of beeves by pressure, and has very similar qualities to the preceding. The tallow is melted, the stearine separated by slow cooling and straining, followed by pressing. The oil is a good lubricant, but is principally used in fine soap-making.

60. **Fish Oils,** so called, include the whale-oils already described, and the oil of the menhaden and other fishes.

Seal Oil is also often classed, even more improperly than the whale-oils, with the fish-oils. It is not a common oil in our markets, and is rarely used for lubrication, although a good unguent.

Porpoise Oil is used as a watch-oil, for which purpose its limpidity and stability of composition well fit it. It resembles the best whale-oils. The "porpoise-oil" of the market is very generally made, not from the porpoise, but from the jaws and

the "melons" of the blackfish. It does not congeal at the zero of the Fahrenheit scale (— 18° C.). It is refined by straining cold. Rusty iron placed in the bottle with the oil keeps it free from acid. It is very expensive. "Grampus" oil is even better than porpoise or blackfish oil. Dolphin Oil, Cod-liver Oil, Dugong or Sea-calf Oil, and the oils of the herring, the sardine, and other fish, have still less use in the mechanic arts.

Menhaden Oil has been used by the author for the preservation of steam-boilers out of use for long periods of time, with very satisfactory results. It forms an impermeable and almost unchangeable greasy varnish, which protects the iron from oxidation very thoroughly.

All these oils, like the animal oils, generally dissolve to a certain extent in alcohol. They are usually extracted by maceration and pressure.

61. The Vegetable Oils are obtained from the seeds, and occasionally from the fleshy part of the fruit, of plants. In one case, that of the earth-almond, the oil is found in the woody tissue of the root. These oils are usually limpid, but sometimes are so hard as to be properly classed as greases. The oils are expressed by grinding the seeds, adding water, and finally treating the emulsion of water, oil, and albuminous matter to separate the oil.

The vegetable oils are divided into two classes, the fixed or non-drying, and the drying oils. The former are permanent liquids, like the animal oils; the latter are subject to a process of oxidation which causes their gumming, and the formation of a resin which is useful as a kind of varnish, and as a vehicle for holding colors in painting. The drying-oils, among which the best known are linseed, castor, hemp-seed, walnut, and poppy oils, are of little value for purposes of lubrication. Castor-oil, when fresh, is a moderately good lubricant for heavy pressures, although the fixed oils are vastly better for common use. It changes much more slowly than linseed-oil.

The non-drying oils, of which the principal are olive, cotton-seed, almond, rape-seed, cocoa-nut, pea-nut or ground-nut, and colza, are all good lubricants. Of these the first named

is by far the best known; although cotton-seed, pea-nut, and colza oils are also extensively used.

The gain in oxygen and the loss of the hydrocarbons in eighteen months, by the process of "drying," is thus shown by analyses made by Cloëz:

LINSEED OIL.

	Fresh. Original weight.	Aerated. Per cent.	Total weight.	Difference.
C..........	77.57	67.55	72.299	− 5.271
H..........	11.33	9.88	10.574	− 0.756
O..........	11.10	22.57	24.157	+ 13.057

CASTOR OIL.

C..........	74.361	72.125	74.058	− 0.303
H..........	11.402	11.108	11.405	− 0.003
O..........	14.237	16.767	17.217	+ 2 980

62. **Olive Oil** is obtained from the fruit of the *Olea Europea*, one of the jasmines, which grows throughout Southern Europe and Northern Africa, and in other semi-tropical countries. The total production of the world is vastly less than the nominal sale, the commercial oil being adulterated to an enormous extent. It is extensively used as a table-oil, as well as for illuminating and lubricating purposes. The finer grades of fruit are harvested by hand-picking, and reserved for the manufacture of table-oils. The larger varieties of olive furnish the less excellent grades of oil which are used in the arts. Each part of the fruit, the outer skin, the pulp, the enclosed seed or nut, supplies an oil of peculiar quality; but they are rarely separated. The oil from the pulp being comparatively free from stearine, remains fluid at lower temperature than that from the other portions of the olive, and is sometimes extracted separately as a watch or a clock oil.

In making olive-oil, the fruit is usually first stored about two weeks in bins, and allowed to ferment slightly, in order that the softened cells may yield their oil the more easily and completely. The fruit is then crushed in an "edge-roller mill," and the oil removed by exposing the pulp so produced

to heavy pressure while enclosed in bags and under a screw-press. The expressed oil runs into tanks of water, and is then separated by skimming. The "virgin-oil" is that which first comes off or often that which drains, unpressed, from the crushed paste at the roller-mill. That which is afterward obtained is called "ordinary oil." An inferior quality is obtained afterward from the mixture of water and paste, which is left to settle in a large reservoir called "*l'enfer*," and this oil is therefore called "*huile d'enfer;*" it is used for a cheap lamp-oil.

Good olive-oil is limpid, unctuous, sometimes colorless, but usually golden yellow or greenish yellow in color, transparent, and if fresh very slightly odorous. Its taste is sweet and fruity, and pleasant to the palate of many persons; but it becomes disagreeable and is unpleasantly odorous when it becomes rancid with age. Its density varies, according to Saussure, from about 0.92 at the freezing-point to 0.86 at the boiling-point of water. It congeals at a low temperature, depositing flakes of stearine as it approaches the freezing-point. Heated, it begins to change to a darker color at about 248° F. (120° C.), and fumes at 356° F. (180° C.), without decomposing, however, as a mass; it must be heated to a considerably higher temperature before breaking up.

All the burning and lubricating varieties of olive-oil are obtained after removing the virgin-oil and finer grades of ordinary oil. They are allowed to remain stored, and are kept warm in tanks for some months to precipitate all foreign substances: they are thus easily and rapidly clarified in summer, less rapidly and perfectly in winter. Good olive-oil is the best vegetable lubricant. Exposed to air, it shows symptoms of rancidity in a single day. It is much more viscous than sperm, and less so than neat's-foot oil. The best olive-oil is, for some purposes, equal to sperm; and it is even claimed to be superior. Good olive-oil is one of the most perfectly non-drying of all the oils; it experiences no other change with long exposure to the air than an increase of viscosity, only slightly observable, according to Cloëz, after a year and a half; it is then increased in weight $3\frac{1}{4}$ per cent.

63. **Cotton-Seed Oil** has been produced since about 1856, in large quantities, in the United States, from the seed of the common cotton-plant as removed from the "boll" by the "gins." It is obtained by crushing the seed and expressing the oil, very much in the same way as other seed-oils. It is, in large quantity, of a dark reddish yellow, and of a rather deep-yellow color in smaller masses. It has a pleasant taste, is to some extent a slightly drying oil, and is used in adulterating non-drying lubricating oils, in making soaps, and for illumination.

This oil is nearly as permanent as olive-oil; Cloëz exposed it to the air for a year and a half without observing other change than a slight loss of fluidity.

The crude oil may be refined by Dotch's method by stirring several hours, with three per cent. of its volume of caustic-potash lye, of 45° B., or with six per cent. soda solution of 25° to 30° B., for an hour, at the boiling-point of the lye. Yellow, clear oil, of density 0.926, separates from a brown soap-stock, and is decanted. Forty gallons of oil are made from a ton of seed: this is about one half the oil contained in the seed, which averages about 25 per cent. oil, by weight.

64. **Rape-seed Oil** is expressed from the seeds of the several kinds of brassica, of which *Brassica napus* and *B. rapæ* are the principal. The seeds are pressed dry, and are sometimes first heated to coagulate the albumen. The crude oil is subjected to a purifying process before it is ready for the market. Clarification is effected either by the use of sulphuric acid, as in Thenard's process, or by chloride of zinc, as in that of Wagner. In the latter case a solution of the chloride, of the gravity 1.85, is used in the proportion of 1.5 to 100 of the oil. After shaking, and then allowing settling to go on for some days, the chloride is removed and the oil cleared by passing into it hot water and steam. The oil is also purified by the Deutsch method of heating to the verge of decomposition, allowing it to boil some hours, and finally skimming and decanting after cooling and settlement have taken place.

Rape-seed oil is of light-yellow color, peculiar taste and odor, and is extensively used in manufactures as well as for lubrica-

tion. The English seed is said to yield the best oil. Its specific gravity is usually 0.913 to 0.917.

65. **Colza Oil** is expressed from the seeds of the wild-cabbage, *Brassica oleracea*, and is largely used for illumination and to some extent for lubrication in Europe, and may ultimately have importance in the United States, as the plant is hardy, and can be successfully cultivated in North America, The oil is considered by some authority to be equal to olive-oil, either as a table-oil or for industrial purposes. It has displaced sperm-oil in many of its applications, and is superior to the latter for illumination; colza is also much less costly than sperm-oil.

Colza-oil is reported by Stephenson* to remain fluid at a lower temperature than sperm-oil. It is an excellent lubricant. If exposed for a long time to the air, this oil thickens slightly, but not sufficiently to class it with the drying-oils.

66. **Palm Oil** is an excellent lubricant, and one of the most valuable of the oils. The principal source is the district lying south of the Volta, on the west coast of Africa, from which section and from South America over a hundred millions of pounds are supplied annually—principally to Great Britain. Large quantities also come from the East, and some from the West Indies. It is used in manufactures, and to a limited extent as a lubricant. The "oil-palm" is the *Elæis guineensis.*

The process of manufacture is quite similar to that of making the seed-oils. The nut-kernels are crushed, or the oil is obtained by boiling in water and skimming the oil from the surface as it collects.

Oils are also obtained from several palm-nuts, as the *Avoira.* The fruit of the latter is small, yellow, pulpy, and contains a nut, "pit," or stone. An oil is obtained from the pulp, and another oil from the nut. The first is yellow, always liquid in warm countries, and is that usually termed "palm-oil;" the second is a solid, white, butter-like fat, often called "palm-butter," or, erroneously, cocoa-nut butter, or cocoa-nut oil. It is rarely sold in the market. The first of these oils is that used in soap and candle making.

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* Commission of Northern Lights of G. B. A. Stephenson, 1857.

The palm-oil of commerce is, when cold, a butter-like solid, orange yellow, sweet to the taste, and of a pleasant violet odor. It melts at 80° to 95° F. (27° to 35° C.), accordingly as it is fresh or old. The liquid oil is dark yellow or orange in color. It saponifies readily, making a yellow soap, extensively used as a toilet-soap. The composition of this fat is, nearly, stearine 31, oleine 69, or, according to Ure, principally *palmitin*, with a little oleine.

The palm-nut oil of Mexico, the coquito-oil, is said to gum very slightly and to be very economical.

67. **Cocoa-nut Oil** is, properly, one of the palm-oils. The nut of the cocoa-palm yields two kinds of oil, the one from the fresh pulp of the nut, the other from the pulp after decomposition has commenced. The first and best oil is made by grating the fruit and expressing its milky juice, from which the oil is obtained by boiling and decanting after settling. The oil is, when cold, white, wax-like, and melts at 70° F. (21° C.). It is composed principally of a peculiar fat, *cocinine*, with a little oleine. When fluid it is colorless; but small quantities of solid fat lie at the bottom when near the temperature of solidification.

The second grade of oil is obtained by heating the partially decomposed pulp in tanks of water exposed to the sun, and skimming off the oil as it rises to the surface. The oil is removed and heated to the temperature of boiling water, to drive out any water that it may contain, and is then ready for the market. It is brown, of rather rank odor, and contains some fat-acids, products of fermentation. This oil is one of the most permanent of all the vegetable oils; eighteen months exposure to the air, according to Cloëz, caused no visible alteration.

68. **Elaine Oil,** so-called by Chevreul, or *Oleine*, is the light oil obtained from tallow and other hard fats, either by pressure or by heating, leaving the more solid part, stearine, behind. It can be obtained from olive and some other oils by cooling, to solidify the heavier fats, thus leaving the oleine to be expressed. The oleine from olive-oil is greenish yellow in color, and frees all margarine at a temperature of about 57° F. (14° C.).

69. **Pea-nut Oil**, or Ground-nut Oil, is obtained from the pea-nut or ground-nut, the fruit of the *Arachis hypogæa*, a small low plant or vine indigenous and common in tropical and sub-tropical North America. The fruit or seed grows upon the root, and is enclosed, usually two kernels together, in a grayish-yellow, woody shell or pod. It has a disagreeable taste when raw, but a pleasant, sweet taste when roasted. The oil is used for the same purposes as olive-oil, which latter is sometimes adulterated with it. It is a good lubricant. The color is light greenish yellow, its gravity 0.916; it is slightly soluble in alcohol, and has a barely perceptible odor. It solidifies at about 34° F. (1° C.) without alteration. It is not a noticeably drying oil, although it thickens a little with long exposure to air.

70. **Castor Oil** is derived from a plant, *ricinus*, known from the earliest historic times as a native of India, but which has been extensively distributed through the warmer parts of Europe, and is now well known in America.

The oil is obtained from the seeds by the processes generally used in making the seed-oils. The seeds are first carefully cleaned, and usually moderately heated, and are then pressed in the hydraulic press. The refuse seed left after thus expressing the oil is again worked over to obtain a second-quality oil. The lower the temperature adopted in the process the better the oil. The yield is about sixteen pounds of oil per bushel of seed. The best oil is nearly colorless; lower grades are yellow or brownish yellow; all have a nauseous taste and disagreeable odor. Castor-oil is remarkable for its power of mixing, in all proportions, with glacial acetic acid and with absolute alcohol. It is soluble in four parts of alcohol. 0.835 or 0.850, at 15° C. (59° F.), and mixes without turbidity with an equal weight of that solvent at 25° C. (77° F.). Its specific gravity is 0.97 to 0.98; it congeals at −12 to −13° C. (8° to 10° F.), and becomes solid at −40° C. (−40° F.)

The oil of the first expression is used for medicinal purposes; that of the second for oiling leather, lubricating machinery, and other purposes. It is better for leather than neat's-foot oil, since it is less liable to become rancid. It is

too viscous for use as a lubricant on light work. It is a non-drying oil also, although it thickens slowly on being long exposed to the air.

71. **Linseed Oil** is the most familiar and important of the "drying-oils." It is obtained from the seeds of common flax, *Linum usitatissimum*, by either the hot or the cold processes. The latter gives the best grades of oil; the former furnishes larger quantities of lower qualities. The best quality is light-yellow, the lower grades of a brownish-yellow color; and both are of great value. The oil has a peculiar odor and taste, a specific gravity of 0.91 to 0.94; it solidifies at $-17.5°$ F. ($-27.5°$ C.). It is principally used in mixing paints and varnishes, and in making printer's ink. Its rapid oxidation and formation of resin—"drying," as it is called—is its most valuable property; one which, however, entirely unfits it for general use in lubrication.

72. **The Mineral Oils**, or "Petroleums," are the fluid, bituminous oils obtained from many different localities, but all having the same mineral origin and common characteristics; their type is "rock-naphtha." They are all hydrocarbons, of the compositions C_2H_4 to $C_{30}H_{30}$, and are the more fluid as the proportion of hydrogen increases. On the one side they differ but little from the soft coals, $C_{24}H_{18}O_4$, and on the other side become pure liquid hydrocarbons of low density, as $C_{24}H_{24}$. The solid petroleum compounds are called bitumen and asphalt, and contain oxygen, of which the oils contain little or none. These oils are of inestimable value in the arts, both as illuminating and as lubricating oils. By their cheapness and by the excellent quality of the heavier petroleums, they are becoming the most generally used of all the lubricants, either alone or mixed with other oils.

Springs and subterranean reservoirs of mineral oil, "coal-oil," or petroleum are found in proximity to deposits of bitumen; and often deposits of enormous extent occur in districts containing bituminous coals, or in drainage-areas lying below such coals. Such deposits have been known for ages in India, in Persia, and about the Caspian Sea, and have been known to exist in America since its first settlement. Pennsyl-

vania now supplies the greater part of the petroleum of commerce.

The oil is usually obtained by boring or "drilling" artesian wells, and the oil often spouts from the newly-opened well in enormous quantities—amounting to several thousand barrels per day in some cases.

Pennsylvania petroleum is usually of greenish color; it is fluorescent, and has a specific gravity of about 0.8. It yields on refining 75 or 85 per cent. illuminating and lubricating oil. Oils exceeding 0.83 in density are good lubricating oils; the best have a density exceeding 0.88, or even as high as 0.94. The refining of the oil is a process of distillation by which the light oils or naphthas are separated from the heavy illuminating or heavier lubricating oils.

An oil which evaporates at the rate of 5 per cent. in a day is unfit to be used as a lubricating oil. Such oils are reserved for other purposes. The mineral lubricating oils of commerce may be divided into three classes:

(1) Natural petroleums of considerable density, purified by heating and retention in settling tanks, and finally by exposure to the action of superheated steam.

(2) Rectified Oils of similar character, further improved by the Cheeseborough Method of filtering, under pressure while hot.

(3) "Cylinder-oils" rectified by fractional distillation and chemically improved.

Of these, the first are generally considered the best; their density is greater than that of the other classes, and their fire and flash test are higher.

Cylinder-oils should have little or no organic oil mixed with them: such mixture is an improvement, if not carried too far, in the cases of other mineral lubricants. When the feed-water of engines is returned to the boiler, as when open heaters are used, only pure mineral cylinder-oils should be used.

A mineral oil has also been made having a density of 32 B. (s. g. 0.86), which contains less than one half of one per cent. volatile matter at 140° F. (60° C.), flashing at 380° F. (193° C.), and burning at 420° F. (212° C.). Such an oil usually contains 50

per cent. volatile matter, and flashes not higher than 300° F. (149° C.).

A good mineral cylinder-oil may be obtained with a density not far from 25° B., i.e., specific gravity 0.9, a cold-test approximating to the freezing-point of water, a melting-point within one or two degrees Fahrenheit (or about one degree centigrade) higher, a flashing-point exceeding 550° F. (266° C.), and a fire-test or burning-point considerably higher than this. It contains no acid and no alkali, but it may be dark in color,—usually a dark brown,—and is very viscous and cohesive.

Pure tallow may be used, alone or in a mineral oil, for this work; but it has less wearing power, is liable to gum, is often acid, and costs considerably more than the best oils of the kind above described.

73. **The Well Oils** are those which principally supply the market. Their properties are quite variable. The gravity varies from 25° Baumé to above 50° (s. g. 0.9 to below 0.78), often varying through this whole range in a single locality. The Pennsylvania oils are usually greenish in color; the Canadian oil is often nearly black; that from Mecca, Ohio, is yellow; and the Italian oils are straw-color, sometimes verging on red. These oils average C. 85, H. 15. In some cases volatilization occurs with great rapidity at ordinary temperatures; in other instances it requires temperatures approaching a low-red heat to vaporize them freely. The light oils are as inflammable as alcohol; the heavy oils burn with difficulty.

Light oils are converted into heavy petroleums by the evaporation of their more volatile constituents or by oxidation, thus producing the bitumens.

74. **Shale Oils** are of similar composition with well-oils, and undoubtedly both have a common origin in the decomposition of the vegetation of an early geological age, through the action of heat and pressure. The reservoirs from which the well-oils are obtained are unquestionably supplied by drainage from the carboniferous rocks in which the deposits of early vegetation are contained. Petroleums are found in all geological "horizons" above the eozoic system, but are principally derived from the bituminous shales, which are rich in the pro-

ducts of decomposition of marine plants. These shales have been for two centuries a source of mineral oil, which is obtained by distillation. It was first thus made in France, on a large scale, by Selligue in 1834; and later, "paraffine-oils" were made at Glasgow by Young in 1850; and soon this became a well-established, but not extensive, branch of industry. Since 1860 the shale-oils have been almost wholly superseded by oils from flowing or from pumping wells.

75. **Refined Petroleums** are most generally applied to useful purposes in the arts. The heavier unrefined or crude oils are sometimes used, untreated, as received from the well, for lubricating machinery, and some of them are fully equal to the best of animal or vegetable oils for this purpose; but as a rule, the oil from the well must be subjected to a refining process before it can be safely or satisfactorily made use of for either illumination or lubrication.

By refining by a process of fractional distillation, the light, dangerously inflammable, oils and naphthas are removed from the illuminating and the lubricating oils, and these last are separated; the lubricating oils being too heavy for use as illuminants. By chilling and pressure, the paraffine or mineral wax is removed from the heavy oils, and sent into the market for use in making candles, and for other purposes. The residue after distillation consists mainly of mineral tar, and contains the coloring matters which have come to hold an important place in the arts.

The process of refining, although ordinarily one of fractional distillation at temperatures which are higher as the operation progresses, is often more effectively conducted by the "vacuum system," in which, by a method similar in principle to that of sugar-refining, evaporation of the more volatile constituents is conducted in a closed vessel, nearly vacuous. The distillation is thus carried on at a comparatively low temperature, and the product is found to possess properties unattainable by the older method of breaking up the natural petroleums. The separation of the lighter naphthas and distillates being thus completed, the heavier distillates can be mixed if desired with the product, and the crude oil thus reproduced without its

vapors. Superheated steam is used in heating, and thus all charring is avoided.

The refined oils are divided by Wilson into three groups:

(1) Natural oils of great body, which are prepared for use by settling in tanks at a high temperature and by ordinary filtration to free them from mechanical impurities, and which are subjected to the action of superheated steam to remove any volatile oil which they may contain, and to give them the necessary body.

(2) The same oils, filtered again at high temperature, and under pressure, through beds of animal charcoal, to improve their color.

(3) Pale, limpid oils, obtained by distillation and subsequent chemical treatment from the tarry residuum produced in refining ordinary petroleum for burning oils.

These oils are sold pure by the refiner, and are mixed, frequently with good results, by the "manufacturer" of lubricating oils. The oils of the first class are best, whether used pure or mixed. The finer color observed in the oils of the second class is usually obtained at the expense of quality; their higher price has no equivalent in efficiency. The third class are usually inferior lubricants. When to be used for the cylinders of steam-engines, these oils should be as viscous as possible, consistently with flowing through the cups at the rate demanded to secure effective lubrication. Oils which are perceptibly volatile are dangerous, and are apt also to leave an objectionable residuum.

Pure natural West Virginia oil, 29° gravity Baumé, is suitable for all kinds of heavy machinery, and will remain limpid in cold climates. It is preferred by many consumers to sperm or lard oil. Oil of heavy body, and a fire-test from 330° to 350° F., is adapted for railroad-car axles, heavy machinery, locomotives, or for any purpose where great heat is to be provided against, and for bearings where heavy weight is sustained. It has excellent wearing properties, and will lubricate and keep car-journals and heavy bearings cool when oils of a low fire-test would volatilize. It can be used during all seasons of the year. Properly refined, it is entirely free from sand, tar, and still-bot-

tom impurities. For factory use, high speed, with both heavy and light bearings, and wherever the lubricator is fed to bearings by capillary attraction, it is a good lubricant. Vegetable and animal oils are compounds of glycerine with fatty acids. When they become old, decomposition takes place and acid is set free, and the oils become rancid. This rancid oil will attack and injure machinery. All animal oils contain more or less gummy matter, which accumulates when exposed to the action of the atmosphere, and retards the motion of the machinery. Mineral oil does not absorb oxygen, whether alone or in contact with cotton-wool, and cannot therefore take fire spontaneously, as animal and vegetable oils do.

The consumption of petroleum or mineral lubricating oils is largely increasing. They are used on all kinds of machinery; they are the safest and cheapest lubricators, and generally superior to animal and vegetable oils and greases.

They are safer on account of their non-oxidizing properties and their high fire-test, or the great heat they will resist before vaporizing. They are cheaper in price, and more economical, saving both machinery and fuel. They are more reliable, as they are usually pure, and uniform in quality. They last longer and work cleaner, and are perfectly free from acids and all impurity. They neither gum nor stain materials or the manufacturers' products.

A good lubricating petroleum has been thus made by refining a natural well-oil of 32° B. (s. g. 0.864) to a gravity of 29 to 30 (s. g. 0.88 to 0.875) in winter, and to 27 or 28 (s. g. 0.892 or 0.886) in summer. A good standard is considered by Wilson to be a fire-test of 550° F. (288° C.).

According to Spon,

(1) A mineral oil flashing below 300° F. (150° C.) is unsafe.

(2) A mineral oil losing more than 5 per cent. in ten hours at 60° to 70° F. (15° to 20° C.) is inadmissible, as the evaporation creates a gum, or leaves the bearing dry.

(3) The most fluid oil that will remain in its place, fulfilling other conditions, is the best for all light bearings at high speeds.

(4) The best oil is that which has the greatest adhesion to

metallic surfaces, and the least cohesion in its own particles: in this respect fine mineral oils stand first, sperm-oils second, neat's-foot oil third, and lard-oil fourth; consequently the finest mineral oils are best for light bearings and high velocities. The best animal oil to give body to fine mineral oils is sperm-oil; lard and neat's-foot oils may replace sperm-oil when greater tenacity is required.

(5) The best mineral oil for steam-cylinders is one having a density of 0.893, and a flashing-point of 680° F. (360 C.).

(6) The best mineral oil for heavy machinery has a density of .880, and a flashing-point of 520° F. (269° C.).

(7) The best mineral oil for light bearings and high velocities has a density of 0.871, and a flashing-point of 500° F. (262° C.).

(8) Mineral oils alone are not suited for very heavy machinery, on account of their want of body, but well-purified animal oils are applicable to the heaviest machinery.

(9) Olive-oil stands first among vegetable oils, as it can be purified without the aid of mineral acids. The other vegetable oils which, though far inferior to olive-oil, are admissible as lubricants are, in their order of merit, sesamé, earth-nut, rape and colza, and cotton-seed oils.

(10) No oil is admissible which has been purified by means of mineral acids.

"*Mixed Oils*" consist usually of mineral oils—petroleums of the heavier grades—mixed with some animal or vegetable oil, and usually probably with lard-oil. These oils, if properly mixed, possess the special advantages of both classes. The mineral oil, of which the mixture generally principally consists, is free from liability to "gumming" or "drying" by rapid oxidation, and has also the property of freely dissolving the organic oils, and of holding them in solution in large proportions, thus taking a "body" which the lighter rock-oils often lack. The mixture is thus a good lubricant, and at the same time comparatively inexpensive; it is also a safe oil. The petroleums so used should be the best of refined oils. The best animal oil for the mixture is sperm; lard and neat's-foot are much used, but are not as good: the former sometimes

separates to such an extent as to produce danger of spontaneous combustion where the conditions are right.

A light mineral oil, unmixed with animal or vegetable fatty material, will sometimes permit objectionable wear of bearings, even while reducing friction, to a greater extent than a mixed or a heavier oil having less friction-reducing power. The finest mineral oils may be used without mixing, however, except where their liability to stain goods, as in some cotton-mills, constitutes a serious objection.

A mixture of paraffine and lard oils, forced between the surfaces by the use of a force-pump, will at low speeds carry the heaviest pressures met with under drawbridges.

Mixed Greases are usually applied only to bearings sustaining very heavy pressures. They are generally made up principally of palm-oil or tallow, with lighter lubricants to soften them to the proper degree of consistency, and often with water and an alkali to saponify them, and so to secure solubility. Thus the yellow fat used to grease axles on railways is a mixture of palm-oil and tallow, to which is added a small quantity of soda and some water.

Lubricants compounded of the well-known oils and greases are therefore, as has been stated, very generally employed, the manufacturer selecting and proportioning the constituents in such manner as to secure precisely that set of qualities that he may consider best for the specific application which he may have in view. Nearly all the lubricants sold in the market under trade-names are of this class. This tendency is very generally observed, and the substitution of "manufactured" oils and greases for the unmixed lubricants is everywhere noticeable. The conditions most favorable to success are not yet well-established, and the business of mixing is mainly directed by empirical methods.

76. Purification is practised with sulphuric acid, and then with some alkaline base.

The illuminating oils have a density of from 0.8 upward, and the lubricating oils from 0.85 to 0.88. Their boiling-points are from 340° to 575° F. (170° to 302° C.). The former, "kerosene," is often unsafe from having too low a burning-point. Its cost

is but a fraction of that of other illuminants. An average Pennsylvania oil, according to Chandler, yields:

Gasolene	1.5
Naphtha	10.0
Illuminating oil	55.0
Lubricating oil	17.5
Paraffine	2.0
Loss, gas, coke	10.0
	100 0

According to Professor J. Lawrence Smith, good "kerosene" should have the following characteristics: (1) The color should be white or light yellow, with a blue reflection. (2) The odor should be faint, and not disagreeable. (3) The specific gravity, at 60° F., ought not to be below 0.795 47 nor above 0.84. 36 (4) When mixed with an equal volume of sulphuric acid of the density of 1.53, the color ought not to become darker, but lighter. A petroleum that satisfies all these conditions, and possesses the proper flashing-point, may be regarded as pure and safe.

According to Grotowsky, the petroleums, when exposed to sunlight, become charged with ozone, and lose illuminating quality, gaining in density and become yellower in color. They should be protected from the action of light and air.

Cleansing Oils which have been used is done satisfactorily by first storing in tanks long enough to permit settlement, next filtering, and finally mixing with a hot solution of 10 or 15 per cent. by volume of equal parts carbonate of soda and chloride of calcium, and a little salt, stirring well, and leaving it a week to settle before decanting.

By another method a tank with an agitator is constructed, the tank of wood, lined with lead. Introducing 500 gallons of oil, the agitator is set in motion, and 26 lbs. oil of vitriol are added by a perforated leaden trough, so arranged as to spread it in a shower over the surface of the oil. The agitation should be continued eight hours. The oil is then allowed to stand ten hours, the acid is next drawn off, and the oil pumped into a steaming tank of iron. It is then steamed eight hours,

leading in the steam through a half-inch steam-pipe. Allowing the oil to stand for thirty hours, draw off the water, and pump into receiving tanks (of wood lined with lead). The lead-lining should be "burned," as if soldered it is liable to fall apart.

Filtering oils is often found decidedly advantageous. Oils not so purified by the manufacturer or dealer, or which have been used, should be carefully filtered before introduction into the oil cup. Cylinder-oils of fine quality cannot, strictly speaking, be filtered: they can simply be strained through fine wire-netting, and should, if practicable, be strained warm (about 100° F.; 37.7° C.). The best oils will pass through the finest nettings made. This class of oils should be filtered with especial care, as chips, dirt, or "still-bottom" impurities, entering with the oil, would be likely to do serious harm. Oils not fed by "automatic cups" are less liable to give trouble if unfiltered; but it is better to filter all oils not filtered before purchase, unless they are heavy-bodied mineral engine and machinery oils, which are seldom used again from the "drip-pans." Light oils are often used over and over again, and should be filtered each time. This system also permits that free and copious supply which will be seen later to be a condition of economy of power, efficiency of machinery, and reduction of expense.

Filters consist usually of several thicknesses of "cheese-cloth," strained across the mouth of a can or bucket which serves as a receptacle for the oil, and from which it is drawn by a faucet set several inches above the bottom in order that any sediment that may still be precipitated may not be taken out with the oil. The two or three thicknesses of cloth should not be in contact, but should be separated by an air-space. A faucet at the bottom can be used occasionally to draw off the lower layer of sediment-charged "settlings." Filters may be made of successive layers of wire-netting, muslin, and other cloths, as flannel and hair-felt, with charcoal interposed, and thus an almost absolute purity of oil secured. The proper order is that which passes the oil through the coarsest materials first, the finest last. The lowest diaphragm should be of wire, strong enough to carry all above it.

CHAPTER IV.

LUBRICATION—METHODS OF APPLYING LUBRICANTS.

77. **The Methods of Lubricating** rubbing surfaces are as various as the forms of lubricants and the conditions under which friction is to be reduced, and their proper selection is of essential importance. The lubricants in solid, semi-solid, and liquid forms require different methods of application, and each is used in a different class of lubricating apparatus. The solid lubricants do not flow, do not wear rapidly, and are put in place only at long intervals; and they remain until so greatly depreciated as to compel their replacement. The semi-solid lubricants may be caused to flow by either heat or pressure, and are usually "fed" to the bearing under the influence both of pressure and the moderate warmth which may be felt in nearly every pair of rubbing parts. The liquid unguents flow so freely that reservoirs must be provided in which they are stored in conveniently small quantities in close proximity to the rubbing surfaces, and from which by some reliable device they may be supplied regularly and continuously in such quantities as may be needed. In rare cases no lubricant is used, but the heat produced by friction is carried away by conduction and radiation across the journal and bearing, or by a stream of water directed over the heated parts; in still rarer cases water is supplied in such manner that it itself forms the bearing.

The Method of Supply is a matter of supreme importance. The "oil-bath," as shown later, sometimes reduces friction to one tenth the amount observed with the more common methods. In all cases in which oil-cups are used, oil-grooves should be cut from the oil-hole to the farthest portions of the "brass." End-play should also where possible be secured. An oil-pad,

as in railway practice, is better than an oil-cup, and a bath is much better than either.

78. The Use of Solid Lubricants is not as common as that of semi-solids or liquids, but is gradually becoming more general for cases of extremely heavy pressure; while they are not entirely out of use for even very light journals. They are sometimes used dry and without admixture, but oftener mixed with the oils. In the latter case they are applied by the methods to be described later.

Plumbago, or graphite, and soapstone are often used dry—the former in bearings, the latter in various forms of "packing." Plumbago has been used in even the finest lace-making and silk-weaving machinery, as well as on heavy machines, the operator *dusting* it between the rubbing surfaces—usually when the machinery is stopped. It has also been introduced into many of the mixed greases, and into oils; in each case for best effect requiring a careful adjustment of the method of lubrication to the conditions involved in its use. For iron-planing machines it is found to be an excellent lubricant used on the "ways" on which the "table" slides in the dry form; it is applied by dusting it on the "V's" as they are exposed during the operation of the machine.

Metaline, a solid compound, usually containing plumbago, is made in the form of small cylinders, which are fitted permanently into holes drilled in the surface of the bearing, which requires no other lubrication. Various compositions are made for the wide range of pressures and speeds met with in machinery. The "anti-friction" metals, so called, all require lubrication, and are only of special value as being soft and yielding, and accommodating themselves to the form of the journal without danger arising from "cutting" or overheating: even if they are melted out they are easily replaced, and no such serious expense is incurred as where "solid brasses" are used.

79. The Semi-solid Lubricants, the Greases, are applied in most cases by the use of "grease-cups" or "grease-boxes." They are always softened and rendered more or less fluid by increase of temperature, and are thus either caused to flow spon-

taneously, or are rendered soft enough to flow under the application of moderate pressure. In some cases they are laid directly upon the rubbing surfaces, either through holes made for the purpose in the "caps" of the journals, or by placing the unguents at intervals upon parts of that surface which are periodically exposed. As a rule, harder and less fusible greases are used in summer than in winter, the difference being produced by the adoption in mixtures of a larger proportion of the hardest constituents in summer and a smaller proportion in winter, as is illustrated in the compositions given already (Art. 53).

80. The Methods of "Oiling," or of applying the fluid lubricants, are usually practically the same for all kinds of lubricants. On very slow-moving parts, when the pressure is moderate, the application of the oil by hand at long intervals suffices; watches are often kept in good running order if oiled but once in two years or more. Fast-running machinery must be frequently oiled, and is generally and should be always so arranged that the supply may be made continuous. In exceptional cases special provision—as by oil-pumps—is made to secure certainty of continuous and liberal supply. The most usual method of continuous lubrication is by the use of "oil-cups"—small metal or glass reservoirs mounted generally upon the piece to be oiled, and supplying the oil through a small channel along which it is "fed" by some device, bringing into play capillary action, as by a wick or by a loosely-fitted wire in the manner to be described presently.

Economy is best secured where the dripping oil is not preserved by any arrangement which furnishes the lubricant in a perfectly uniform supply and in minimum safe quantity. In some cases "self-oiling" boxes are used with good results; in these arrangements the oil is contained in chambers or reservoirs in close proximity to the rubbing surfaces, and in sufficient quantity often to require renewal only at intervals of several months. Where this system involves the oil-bath, it is probably best of all. Careful management of the ordinary system of oiling with the common oil-cup will, however, give equal economy of oil: the line-shafting of a large machine-

shop has been kept running for long periods of time with an expenditure of but 17 drops of sperm-oil per bearing per week. The reduction of friction is not as effective, however, as in the preceding case.

Uniformity of distribution is as important as uniformity and continuity of supply. A dry spot occurring on the journal will immediately cause heating and "cutting." The oil should therefore be led upon the journal in such a manner as to insure that every part shall be reached and kept well lubricated. The method of oiling, as well as the quality and kind of lubricant, should be adapted to the special case in hand.

Since the lubricant is not itself worn, and undergoes no physical change while in use, and no other chemical change than that of gumming by exposure to air, a flooded journal with an effective system of collecting and reapplying the outflowing oil, with occasional purification as may be necessary, gives maximum economy both of power and of lubricant.

Steam-cylinder lubricants are best supplied by the "automatic" feed-cup, of which many varieties are made, and among which some few serve their purpose admirably. The form used for this purpose should be capable of supplying the heaviest and darkest of mineral cylinder-oils, and with perfect uniformity and certainty at minimum rates of flow. The "sight-feed" cups, in which each drop of oil is seen as it passes from the reservoir through a glass feed-tube to the steam-pipe, is a form which has the double advantage of doing its work well, and of at all times doing it in view of the attendant. The cup used should be as carefully kept in order as the engine itself. The rate of feed is usually made a minimum, and with good lubricants can be reduced to 4 or 5 drops per minute per 100 horse-power of engine, and perhaps somewhat lower still with engines of more than 100 horse-power.

Mineral cylinder-oils, when used after the habitual use of animal or vegetable oils, will gradually dissolve the gum already deposited in the cylinder and its passages, and will later work well and keep the cylinder clean. Some loss of efficiency may be noticed in the interval. If the gum is thrown off in masses, as sometimes happens, it may give

trouble; and it is much better to carefully inspect the cylinder and remove any that may exist before danger can arise. This process may occupy weeks, and is a particularly slow process after tallow has been long used.

Lubricants used in bolt-cutting demand the same qualities as for other cases of lubrication, and in considerable degree their choice is similarly determined. That oil which will give the smoothest cut and finest finish with minimum expenditure of power is cheapest as a rule, whatever may be the market price. The best lard-oil is commonly used for this purpose; mineral oils are also used.

Recent investigations show that, contrary to earlier opinions, the best method of using oil, and particularly on fast-running machinery, is to supply it as freely as possible, and receiving the rejected portion, reapply it after thoroughly filtering it if necessary.

The heavy mineral oils only should be used in steam-cylinders and on hot rubbing surfaces. The best of animal and vegetable oils will decompose, and will corrode metal so rapidly as often to cause serious expense, even where they might be otherwise desirable unguents; their fatty acids are dangerous constituents, and their liability to gum is a source of danger as well as of expense.

In textile manufactures the relative value of oils and expense of operating is influenced to an important extent by the greater or less liability of the oils used staining the fabrics made, and this consideration alone will often determine a choice of oils without regard to price.

81. The Forms of "Grease-Cup," or of "tallow-cup," used in applying the semi-solids and the more fluid greases are usually all of one class. A reservoir, box, or cup is placed in contact with the bearing to be lubricated, and is filled with the grease, tallow, or other semi-solid unguent: the lubricant settles down gradually upon the bearing, through an opening of usually quite large section; or it is forced through a smaller passage under the pressure produced by a weight or a spring. In some cases the reservoir is formed in the "cap" of the bearing, and a slot cut down through the cap allows the unguent to

settle down slowly upon the journal: with soft tallows and greases this provision is ample, and the stored lubricant is only drawn upon when the bearing is at that temperature which, if the adjustment is correct, gives at once minimum friction and maximum economy.

Grease-cups similar in form and in method of attachment to the common oil-cup are sometimes used, as in the figures, which illustrate the construction of two such cups.

The first form of cup (Fig. 20) is placed in the vertical position, and the weight of the piston and of any material with which it may be loaded forces the grease into the oil-channels.

FIG. 20.—THE WEIGHTED LUBRICATOR-CUP.

FIG. 21.—THE SPRING GREASE-CUP.

The body of the cup is of glass, and permits the flow of the grease to be conveniently watched. When first applied, the unguent is forced into the journal by pushing down the piston a little way by hand. The second style of cup (Fig. 21) is set in any convenient position, and the "feeding" is accomplished by giving the cap a slight movement by hand once a day or once a week, according to the character of the work. Forms of cup are sometimes used in which the movement of the piston in the first-described grease-cup is effected by a screw.

With journals not covered by "pillow-block caps," these contrivances are not needed: the grease or tallow is laid directly upon the journal, and if sufficiently hard and cohesive, works satisfactorily and with economy.

82. The Forms of Oil-cup in common use are very simple in construction, and are, if properly adjusted to their work, economical. Whatever the form of cup, if the flow of oil can be made uniform and in minimum quantity consistent with safety, and with perfect certainty of continuous supply, maximum economy can be attained.

The most common form of oil-cup consists of a small metal

FIG. 22.

FIG. 23.

NEEDLE LUBRICATORS.

or glass vessel or vase fitted with a central tube rising nearly to its top, and opening downward into the oil-hole, into which the supporting stem of the cup is screwed. "Wicking" is twisted into a loosely laid-up cord, which is entered into this vertical tube, one end hanging down below the level of the bottom of the oil-cup, the other lying over the top of the feed-tube, and dipping into the reservoir of oil. The Author has sometimes coiled such loose strands of wick loosely about a bent wire, one end of which dips into the cup, the other into the feed-tube: this can be removed when the machinery is at rest, and replaced before starting; thus, in the operation of marine or other intermittently operated engines, effecting an observable economy.

The "Needle Lubricator" (Figs. 22 and 23) consists of a

reservoir fitted with a central delivery-tube, terminating a little above the bottom of the reservoir, and itself nearly filled with a loosely-fitted wire, the lower end of which reaches down to and rests upon the journal to be oiled, while the upper end rises into the mass of oil with which the cup is filled.

There is no flow of oil while the machinery is at rest. Being perfectly air-tight, the oil will not gum. The size of the wire is reduced if the oil is desired to "feed" more rapidly. As the flow is produced by the vibration of the shaft and con-

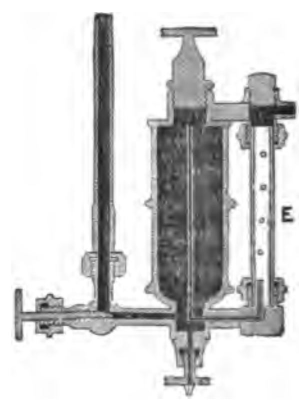

FIG. 24.—ELEVATION. FIG. 25.—SECTION.
SEIBERT SIGHT-FEED OIL-CUPS.

sequent jar of the wire or "needle," the rate of feeding is to a certain degree self-regulating. When the machinery is stopped, capillary attraction prevents flow, and there is no waste of oil.

When lubrication is to be secured in steam-spaces, as in the valve-chests and cylinders of steam-engines, special forms of oil-cup are used, which are often called "self-acting lubricators." In these, the cup is provided with a central tube, which rises nearly to its top, and which has on one side a hole through which the oil may find its way into the tube and down into the chamber to be lubricated. A screw-cap is fitted air-tight.

The oil is introduced, the cap screwed firmly down, and the cock below opened to permit free communication with the steam-space. Steam fills the cup at full pressure; as it condenses the water falls drop by drop to the bottom of the cup, each particle displacing a drop of oil, which flows through the hole into the central tube, and down into the steam-chest. Such an apparatus has been found sometimes to reduce the expenditure of oil to one fourth, and even, in exceptional cases, to one tenth the amount used with ordinary hand-supply.

In some cases, as illustrated above (Fig. 24), a glass gauge is attached, to show the level of the surface of contact of the oil and the water; and in other cups a pipe leading to the main steam-pipe, to furnish a means of securing a more rapid flow of oil if needed.

These instruments are sometimes called "hydrostatic lubricators." Such lubricators are often so arranged that the oil may be seen rising drop by drop through water, as in Fig. 24, in which *B* is the oil-feed pipe to the engine, *D* the cup, *E* the glass "indicator" up which the oil rises, *F* the condenser supplying water by condensing steam. This forms what is often called a "sight-feed" cup, or lubricator.

Another cup (Fig. 26) has a similar general arrangement. *E* is the steam connection, *AJ* the cup, *D* a glass water-gauge which shows water when the oil is low, and the feed-chamber has a guide, as shown, to direct the drop.

The automatic "sight-feed" lubricating apparatus is usually much more economical than any "hand-feed" can be, and in some cases has been known to save nearly one half the oil demanded by the latter method on railway passenger-trains, and a third on freight-service. It should preferably be placed between the throttle-valve and the boiler.

Feed-cups for steam-cylinder lubrication are best when so constructed that the drops can be seen plainly and as far away as possible. The drop should be cut off squarely, and at exactly equal intervals. The larger the drop, as a rule, the better, and the more certain is it to flow with regularity and certainty with the best and heaviest oils.

One of these lubricators is shown in Fig. 27 as attached to

the steam-pipe by the steam and discharge pipes, *A* and *B*. Steam condenses in *F*, filling it and displacing the oil in *D*, which flows up through *E* to the steam-pipe and the engine.

83. Machinery in Rapid Motion, and especially rapidly

FIG. 26.—CRAIG AUTOMATIC SIGHT-FEED LUBRICATOR.

revolving parts, are sometimes very difficult to lubricate. The crank-pins of fast-running steam-engines are examples of such cases, in which also perfect lubrication is of vital necessity to the successful operation of the machine. In such cases special devices are often adopted. One usually satisfactory but some-

what costly device is that of drilling oil-passages from the body of the shaft out, through the crank, and then into the pin, finally leading the oil out laterally to its surface, thus taking the oil in at a point which is comparatively accessible, and taking advantage of the action of centrifugal force to carry it forward to the surfaces to be reached. Overhung pins are often fitted with a lubricating device consisting of an ellipsoidal

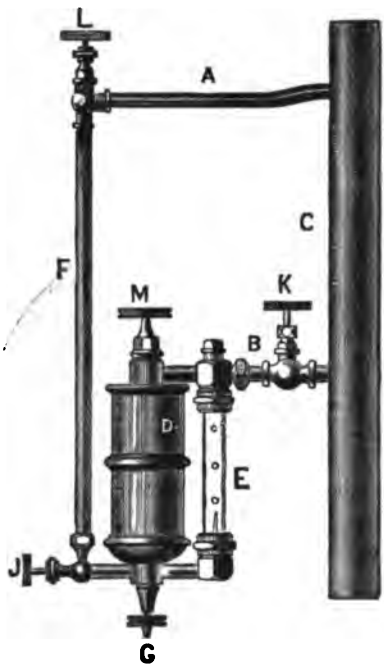

FIG. 27.—SIGHT-FEED ATTACHED.

or spheroidal oil-reservoir placed in the line of the axis of the shaft, and carried by a tube connecting it to the end of the crank-pin. The oil is introduced, in any convenient manner, into an opening at the axis of the reservoir, and finds its way outward through the carrier-tube and thence into the pin and to its rubbing surfaces. The common oil-cup is often used as a feeder to the reservoir. Another method (Fig. 28) is that adopted by Messrs. Armington & Sims.

84. Oiling by Hand is practised both in lubricating rubbing parts easily kept in order, and oftener in filling oil-cups at intervals, and renewing their contents as expended. The common hand "oil-can" is a reservoir usually of brass or tin fitted with a spout from which the contained oil may be conveniently poured in as small quantities as may be desired. It is made large enough to hold as much as it is found convenient to carry, and is principally used to supply smaller receptacles and oil-cups.

The "Oil-feeder," or "Oil-can," or "Squirt-can," as it is variously called in the shop, is a conically-shaped vessel, small enough usually to be carried conveniently in one hand, which

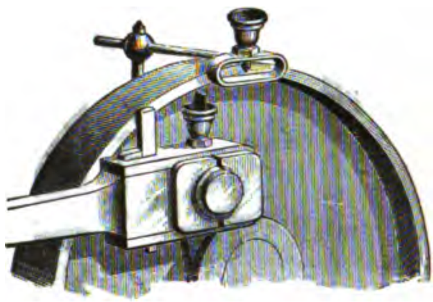

FIG. 28.—CRANK-PIN LUBRICATOR.

has a flexible and elastic bottom; while at the upper and smaller end of the cone a tapering tube is screwed which has a very small orifice at its extremity. This little instrument being filled or partly filled with oil, held between the middle fingers and inverted, the pressure of the thumb on the bottom causes the oil to spurt from the point of the tube in a fine jet, which is directed to the point at which the oil is needed.

85. "Oil-Pumps" are sometimes used where the bearing to be lubricated is either peculiarly important, as the steps of vertical shafts or the "thrust-bearing" of a steamship, or where it is unusually liable to heat. In such cases a reservoir of considerable volume is placed in a convenient location and nearly filled with oil, a pump connected by its suction-pipe with this reservoir, and by a force-pipe with the bearing, is kept in operation

by connection with the mechanism to be oiled, and an ample and continuous supply is thus secured. Even this arrangement is liable to failure, and to cause the very accident that it is intended to prevent if the oil used is not absolutely free from foreign material, if the connections are not all well made, if the valves of the pump leak or fail to seat properly, or if the pump-plunger is not kept well packed.

86. **Water-Bearings** have been adopted in some cases, as by Shaw and by Giffard,—the "*paliers glissants*" of the French engineers,—in which the weight of a revolving shaft is taken by a cushion of water, or sometimes of oil, and in which the journal does not bear upon metal at all, except as it may be necessary to steady it. The journal enters a bearing so constructed that the liquid can be forced between the two adjacent surfaces in such quantity and under such pressure that the journal is supported by and turned upon the fluid cushion so formed. The excess of the liquid which flows out at the end of the bearing returns to the reservoir below, and is again circulated by the pump. Journals thus arranged have been known to work many months without appreciable wear, and even without discoloration of the liquid.

87. **Unlubricated Bearings,** cooled usually by the flow of water across them, are sometimes found preferable to any other device for sustaining parts having relative motion under pressure. Thus the "stern-bearings" of screw-steamers are almost invariably fitted up in this manner. The screw-shaft of iron or steel is encased in brass and turns within a long, hollow, cylindrical sheath, which is fitted with narrow strips of lignum-vitæ, separated by longitudinal spaces forming water-channels. No lubrication is employed, and the bearing is kept cool by the flow of water between the strips of lignum-vitæ. Such bearings wear well in clear water, but cut away rapidly in shallow water over sandy bottom. The lignum-vitæ if kept cool will sustain enormous pressures, and will wear in such situations better than metal.

88. **Bearing Surfaces** are of bronze or other alloys, of cast-iron or other metal, or of wood, according to location, intensity of pressure, velocity of rubbing, and nature of the

material of the journal. Ordnance bronze wears well under heavy pressures and at high speeds if not subjected to intense localized pressures by the springing or misfitting of parts; cast-iron has an advantage, if used under moderate pressures and in ample extent of surface, in its porosity and absorptive power and the persistence with which oil and grease adhere to it; wrought-iron and steel sustain heavy loads, if free from surface defects; "mild steel" is peculiarly valuable for journals, and hard steel ground to shape and well bedded in its bearing will safely carry pressures of enormous intensity; wood is only used in special cases. Too high a polish on the harder surfaces is objectionable where thin oils and heavy pressures are adopted, as the lubricant is difficult to feed between the metals in contact, or to keep there while in operation.

It is nearly always advisable to make the bearing of the softer metal, since its renewal is a matter of less difficulty and expense than that of the journal, and since the journal must usually have great strength. A hard bearing cuts the softer journal, and gives rise often to serious expense. It is from this consideration that bearings are often "babbitted" or lined with the soft white alloys.

The fitting of the surfaces in contact is as important a matter as the selection of the material of which they are composed. The theory of friction is based upon the assumption that all parts are accurately made to correct dimensions, and exactly fitted; and the conclusions derived are therefore invalidated by any departure from such assumed conditions. Precision and stability of form—stiffness of all loaded parts—are essential elements of successful working. Stability of form is dependent upon extent of surface exposed to wear: if this area is ample, so that the two rubbing parts nowhere and at no time come into unrelieved metallic contact, no appreciable wear will occur, and their forms will be permanent.

Surfaces of similar area and form, even when well fitted, if of different materials will wear very differently. Thus the following table shows the comparative wear of axle-bearings. Thoroughly pure bronzes, like those fluxed with phosphorus,

were reported as wearing very much less than ordinary compositions.

Bearing.	Composition.			Cost per 100 lbs.*	Miles run per lb.	Wear per 100 miles for four bearings.
	Copper.	Tin.	Antimony.			
Gun metal	83	17	..	$28 60	25,489	200 grs.†
" "	82	18	..	28 68	27,918	252 "
White-metal	3	90	7	32 85	22,075	366 "
" "	5	85	10	32 27	24,857	284 "
Lead Composition: lead, 84; antimony, 16	..	..	..	13 04	22,921	308 "
Gun-metal on brake-cars	82	18	..	28 68	2,576	274 "

In many cases the excessive wear of a bearing is due to a misfit. The Hopkins bearing is a bronze bearing lined with a thin layer of lead, which, when new and unfitted, can accommodate itself to the distorted journal and permit gradual wear to a correct fit without danger of injury, such as occurs often with the common hard, unlined "brass." In the Defreest bearing a thin bronze bearing-piece is sustained by a strong iron backing-piece, and between them is a sheet-lead filling. Journals should be fitted without the use of emery or other gritty grinding material, which may adhere to its surface and thus produce injury.

Bearing Surfaces of Wood are, under the conditions already described as favorable to their use, exceedingly durable, and will carry enormous loads without abrasion. Thus lignum-vitæ will sustain pressures exceeding 1000 lbs. per square inch (70 kgs. per sq. cm.), where brass becomes rapidly abraded and destroyed under but little more than one fourth of that load, and will run continuously under 4000 lbs. (281 kgs. per sq. cm.) when bronze sets fast instantly. Camwood has been subjected to pressures exceeding 8000 lbs. per square inch (562 kgs. per sq. cm.), and has worked without injury; snakewood carries about as heavy a load as lignum-vitæ.

* Including melting expenses, loss, etc. These figures are constantly varying.

† Seven thousand grains per pound.

The bearing surfaces of watch-work are often made of ruby, agate, and other fine-grained and hard stones, and of gems.

A comparison made by the author between surfaces of gun-bronze, of "Babbitt"-metal, and of other soft, white alloys, all working on steel, proved all to have substantially the same friction. In other words, the coefficient of friction was determined by the nature of the unguent and not by that of the rubbing surfaces, when the latter are in good order. The soft metals, however, heated more than the bronze, running at temperatures somewhat higher with equally free or even freer feed. To retain the temperature at 135° F. (57° C.), in some cases one half more oil—over 300 grammes, as against 200—was needed on the white metal than on the bronze. This probably does not, however, necessarily indicate a serious defect, but simply deficient conductivity. Lined journals may be expected to run normally warmer than unlined bronze of good quality. The following are the results of experiment with a "Babbitt"-metal, which was compared with bronze and a second white alloy:

	Bronzes.	White Metal.	
		No. 1.	No. 2.
Mean Temperature, Fahr.......	133°	152°	137°
Mean Coefficient of Friction.....	0.010	0.013	0.010
Oil used per hour, ounces........	7	17	12

These differences prove ordinary lubricated surfaces to have contact, since they give differences in the values of f where none could exist were the friction fluid-friction solely.

CHAPTER V.

THE INSPECTION AND TEST OF LUBRICANTS.

89. Systematic Methods of Examination of Lubricants are always necessarily adopted by large consumers of lubricants. The opportunity for adulteration is so great, and a mistake in purchasing is so liable to result in serious accidents and large expenses for repair, or for wasted driving-power, that very considerable expenditure of time and money is often justified in the endeavor to secure reliable determinations of the quality of the unguent which it may be proposed to use. These methods of test are often physical, sometimes chemical; and very frequently they consist of direct methods of determination of the value of the oil in reducing friction, and of its durability under wear and under the conditions of every-day work.

Of these tests the simplest is the measurement of the density of an oil; any variation from that of known pure oils of the same nominal grade being evidence of adulteration or of probably low quality. The method to be described as "oleography" is another physical test, and the so-called "fire-tests" are other illustrations of this class. The chemical tests are usually processes of qualitative analysis, and the last-mentioned systems of test are generally practised by the use of "testing-machines," forms of which will be described later.

The density of the oils is always less than that of water, and varies from 0.875, that of sperm-oil, to 0.99, that of the heaviest rosin-oils. The gravity of the oil, except perhaps in the case of sperm, is not a definite gauge either of the nature or of the quality of a lubricating oil, as mixtures may be made of any desirable density. There is also no direct relation between their lubricating property and their density.

much the same manner as does the application of heat; and their action is accompanied by the development of heat, the amount of which is an indication of the nature of the oil. The reactions of sulphuric and of nitric acids have been very thoroughly studied. Chlorine and iodine have also been much used in this work. The action of the oil on metals, as on copper or brass, is indicative of the presence of acid in the oil; the amount of this action, as evidenced by alteration of color, is a gauge of the quantity of acid present. Acid is not found in pure mineral oils. Sperm and neat's-foot oils, and tallow, are very often acid either from chemical alteration or from the introduction of foreign compounds having acid reactions.

Professors Crace-Calvert, Cailletet, Chateau, Wurtz, and many other chemists have systematically studied the reactions of oils with various chemicals, with a view to their identification and the detection of adulteration.

When, without any previous knowledge of the nature of any substance, it is proposed to discover all its constituent parts, and to furnish a proof that, besides the elements exhibited by analysis, it does not contain others, it is necessary to proceed with a method, and to follow strictly a systematic plan. Methods of analysis may be numerous and of various kinds, but they are founded upon the same principles and all present the same character. In fact, in *all* methods of analysis certain reactions are made use of, which enable us to divide all bodies, or all those under consideration, into classes that are perfectly defined. Such characteristics are always made use of that each of these sections shall comprise, as nearly as possible, equal numbers of bodies which exhibit in the same degree the reactions which have served to establish the group. By another set of characteristics, new divisions and subdivisions are established in each of these classes. Proceeding in this way, a certain number of substances are eliminated, with which we need no longer occupy ourselves; and after some tests, usually but few in number, we acquire the knowledge that the elements of the composition submitted to analysis belong to such or such section or class, or to one of the divisions or subdivisions.

It is only after having arrived at this result that we seek to

determine by a special method the body considered, by making use of specific characteristics and particular reactions.*

92. **Chateau's Methods**† are among those which by general reactions form such classifications as facilitate the determination of the nature of the oil, and consequently allow its purity to be judged.

These general reactions are—

(1) The use of bisulphide of calcium, giving a soap which remains colored or loses its color.

(2) The colors given with the sirupy chloride of zinc.

(3) The colors produced by ordinary sulphuric acid.

(4) The colors produced by forming bichloride of tin.

(5) The colors given, both cold and warm, with sirupy phosphoric acid.

(6) The colors given by the pernitrate of mercury employed alone or together with sulphuric acid.

These general reactions are rendered complete by the use of several other reagents, potassa, ammonia, nitric acid, etc., the use of which will be stated in the monography of the fats. Finally, the nature of the oil will be ascertained with certainty by testing for special characteristics and particular reactions. The tests may be made in a large watch-glass placed on a white paper, on a glass plate; also on white paper, or in a small white porcelain capsule. In practice the watch-glass has been preferred.

93. Preparation and Use of the Reagents.

Bisulphide of Calcium.—This is easily prepared by boiling a mixture of flowers of sulphur with chalk and water. After boiling a half-hour it is filtered. That which has been prepared several days is to be preferred.

Chloride of Zinc (*sirupy*). — This reagent is prepared by saturating pure hydrochloric acid with oxide of zinc and evaporating to dryness. A sirupy aqueous solution is made of the product.

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* Précis d'Analyse Chemique Qualitative. MM. Gerhardt et Chancel.

† Guide Pratique de la Connaissance, et de l'Exploitation des Corps Gras Industrielles. Theodore Chateau Paris, 1864.

Sulphuric Acid (*commercial and colorless*).—This acid is used in the proportion of 3 or 4 drops to 10 or 15 drops of oil.

Bichloride of Tin (*fuming*).—This reagent is obtained from dealers in chemicals. It is also called the "*fuming liquor of Libavius.*"

Phosphoric Acid (*sirupy*).—A strongly concentrated solution resulting from the action of nitric acid upon phosphorus, or else a sirupy solution of phosphoric acid prepared in advance, or, better still, bought of the druggist.

Pernitrate of Mercury. — This is prepared by dissolving mercury in an excess of pure nitric acid. The use of this reagent is twofold: 1st, in the observations of color produced by the salt alone; 2d, in observations of the colors produced by sulphuric acid when poured over the oily mass after the action of the salt of mercury.

Potassa.—Concentrated solution of caustic potassa. Chateau uses alcoholic potassa.

Ammonia.—That of commerce—colorless.

Nitric Acid (*pure*).—Commercial.

All these reagents are employed by pouring a few drops (four or five) on the oil, which is placed in a watch-glass, covering about half its surface.

With the concrete oils, the fats, tallows, and waxes, four or five drops of the reagent are used with a piece of the fat of the size of a pea.

94. **The Reactions of Oils** when they are subjected under similar conditions to the general reagents already indicated are given in the following tables by Chateau.

To facilitate and guide investigation, the oils are divided into mineral oils, the drying and non-drying vegetable oils, and animal oils.

TABLE I.—COLOR REACTIONS OF THE OILS. (CHATEAU.)

BISULPHIDE CALCIUM. Soap, golden-yellow. Permanent.			BISULPHIDE CALCIUM. Golden-yellow soap, losing color quickly on agitation, and becoming canary-yellow or pale yellow.		
DRYING.	FIXED.	ANIMAL.	DRYING.	FIXED.	ANIMAL.
Linseed (English). do. (Northern Europe). do. (Bayonne). do. (India). Poppy (French). Nut (Walnut).	Olive. Sweet Almond. Colza. Rape-seed. Sesame. Camline. Cotton-seed.	Neat's foot. Tallow-oil (or Oleic Acid). (with sulphuretted hydrogen gives a decided dark-gray color.) Sperm.	White Poppy (India). Hemp seed. Castor.	Olive (ordinary salad). Olive (huile d'enfer). Pea-nut. Beech. Olive (refuse), (dense yellow soap, becoming grass green, then greenish white.)	Neat's-foot (Buenos Ayres). Neat's-foot (Paris). Horse-foot. Seal. Fish. Whale. Cod-liver (Dunkirk).

NOTE.—The reagent is added, and with a glass rod stirred into the oil. It seldom requires more than a dozen strokes to cause the golden-yellow color to change, becoming faint-yellow.

CHLORIDE ZINC.

Either white mass, slightly yellow, or no color.			Yellow (Y.), Orange yellow (O.Y.), Flesh-rose (F.R.), Dark brown (D.B.).			Greenish yellow (G.Y.), Green (G.), Bluish green (B.G.).		
DRYING.	FIXED.	ANIMAL.	DRYING.	FIXED.	ANIMAL.	DRYING.	FIXED.	ANIMAL.
Poppy (French) do. (White; India). Nut.	Sesame. Sweet Almond (hot-pressed).	Neat's-foot (Paris). do. (Buenos Ayres). Sheep foot. Horse-foot (cold-pressed). Sperm. Whale (no color). Cod-liver (cold-pressed).	Linseed (English), (Y.) Castor (rose; yellowish).	Rape seed. Pea-nut. Beech (F.R.). Cotton (D.B.).	Horse-foot (yellow hot) Whale (Y.B. hot). Tallow-oil. Fish. Seal (R.B.). Ray-liver (Y.R cold).	Linseed (India). Linseed (Bayonne). Linseed (N. Europe).	Colza. Camline. Sweet Almond (cold). Olive (refined), (greenish). Olive (ordinary). Olive (huile d'enfer). Olive (refuse), (remains green.)	Cod-liver (hot). Ray-liver (hot).

TABLE I.—COLOR REACTIONS OF THE OILS—*Continued*.

SULPHURIC ACID.

Dragon's-blood (D.B.), Dark reddish brown (R.B.), Brownish red (B.R.).			Yellow (Y.), Dark yellow (D.Y.), Reddish yellow (R.Y.), Orange yellow (O.Y.).			Either green veins or green coloration, or becomes greenish by agitation.		
DRYING.	FIXED.	ANIMAL.	DRYING.	FIXED.	ANIMAL.	DRYING.	FIXED.	ANIMAL.
Linseed (N. Europe). Linseed Bayonne). Linseed (India), (with agitat'n.) Nut (with agitation).	Pea-nut. Beech (agitat'd) Cotton.	Neat's-foot (Buenos Ayres), (with agitation.) Horse-foot (agitation). Tallow. Fish (brownish black). Seal (D.B. dark). Sperm (B.R.). Whale (B.R.). Cod-liver (violet-red, crimson, agitated, violet, then D.B.). Ray-liver (do.).	Linseed (India), (O. Y. without agitation.) Poppy (French), (bright Y. and O.Y.) White Poppy (India), (light Y., gold Y., and O.Y.) Castor (bright Yellow, then R.Y.).	Olive (refined), (Y. without agitation.) Olive (ordinary), (Y without agitation, R.Y. with agitation.) Olive (huile d'enfer), Y. then R.Y. Sesame. Beech (D.Y.), (no agitation.) Sweet Almond (Y., no agitation). Camline (R.Y.).	Neat's-foot (Paris), (Y., then O.Y.). Sheep-foot (Y. and R.Y.).	Hemp-seed. Linseed (English), (with agitation.)	Colza. Camline. Olive. Sesame (agit'd). Rape-seed. Sweet Almond (greenish Y., agitated). Camline (green veins).	

FUMING BICHLORIDE OF TIN.—The Coloration takes place Instantaneously.

Yellow, Faint yellow (F.Y.), Golden yellow, No color.			Brownish red, Distinct brown (D.B.), Reddish yellow (R.Y.), Brownish yellow (B.Y.).			Green, Bluish green, Greenish-blue.		
DRYING.	FIXED.	ANIMAL.	DRYING.	FIXED.	ANIMAL.	DRYING.	FIXED.	ANIMAL.
Poppy (French) Castor.	Olive (refined). do. (Ordinary). Sesame (F.Y.). Sweet Almond (no color).	Neat's-foot (Paris). Sheep-foot (F.Y.).	Linseed (English), (B.Y.). Linseed (N. Europe). Linseed (Bayonne). Linseed (India). White Poppy (India), (R.Y.) Nut (R.Y.).	Olive (huile d'enfer), (R.Y.) Pea-nut (distinct B.). Camline. Beech (R.Y.). Cotton-seed, O. Y. (?)	Neat's-foot (Buenos Ayres), (R.Y.) Horse-foot (R.Y.). Tallow (R.Y.). Whale (O.Y.). Sperm (purplish R. B.). Seal. Fish (deep R.B.).	Linseed (English), green veins. Linseed (N. Europe), (bluish green.) Linseed (Bay'e), (bluish green.) Linseed (India), (bluish green.) Hemp-seed.	Olive (*lampante*). Rape-seed. Colza.	Cod-liver (violet blue, reddish violet, violet of pansy, crimson). Dragon's-blood. Ray, same.

TABLE I.—COLOR REACTIONS OF THE OILS—*Continued.*

FUMING BICHLORIDE OF TIN.—Color of the Thickened or Solidified Mass.

Yellow, Faint yellow (F.Y.), Bright yellow (B.Y.). Straw-yellow.			Brown, Distinct brownish red (D.B.R.), Orange yellow (O.Y.), Reddish yellow (R.Y.).			Green, Greenish, Dirty green, Dark green.		
DRYING.	FIXED.	ANIMAL.	DRYING.	FIXED.	ANIMAL.	DRYING.	FIXED.	ANIMAL.
Poppy (French) White Poppy (India). Castor (faint).	Olive (refined), (bright Y.). Sesame. Sweet Almond (canary Y.). Camline (faint Y.).	Sheep-foot (faint, rosy Y.).	Linseed (English), (D.B.R.). Linseed (N. Europe), (brownish gray.) Linseed (India), (R.Y.)	Olive (ordinary), (O.Y.) Olive (huile d'enfer), (R.Y.) Colza. Pea-nut (B.R.). Beech (distinct R.Y.). Cotton (Y.B.).	Neat's-foot (Paris), (O.Y.) Neat's-foot (Buenos Ayres), (O.Y.) Horse-foot (O.Y.). Tallow (does not solidify), (R.B.) Whale (clear mahogany). Sperm (O.Y.). Seal (R.B.). Fish (dark sepia). Cod (dark orange). Ray (dark orange).	Hemp-seed (dark green).	Olive, (crude) (dirty green.) Rape-seed (dirty green).	Ray (Y.G., reddish).

PHOSPHORIC ACID.—Colors Exhibited when Cold.

White, No color, Discoloration, Gray, slightly yellowish.			Yellow, Straw, Golden yellow, Orange yellow (O.Y.).			Green, Greenish, Bluish, Dark Green.		
DRYING.	FIXED.	ANIMAL.	DRYING.	FIXED.	ANIMAL.	DRYING.	FIXED.	ANIMAL.
Poppy (French), (white). White Poppy (India), (white) Nut (white). Castor (white).	Sweet Almond (discolored). Rape-seed (discolored). Camline. (discolored).	Neat's-foot (Paris). Sheep-foot.	Linseed (North Europe). Linseed (Bayonne). Linseed (India), (straw-yellow.)	Sesame (S.Y. and O.Y.). Pea-nut (S.Y.). Cotton (gold Y.).	Whale (S.Y., then O.Y.). Neat's-foot (Buenos Ayres). Horse-foot (O.Y.). Tallow (S.Y.). Sperm (S.Y.) Seal (distinct br. red). Fish (R.Y.). Cod (R.Y.). Ray (gold Y.).	Linseed (English). Linseed (North Europe). Linseed (Bayonne). Hemp-seed (D.G.).	Olive (refined). do. (ordinary) do. (crude). do. (huile d'enfer). Colza. Rape-seed. Camline.	

TABLE I.—COLOR REACTIONS OF THE OILS—*Continued.*

PHOSPHORIC ACID.—Colors Exhibited when Hot.

No Coloration.			Yellow, Gold yellow, Orange yellow, Reddish yellow (R.Y.), Bright yellow (B.Y.).			Froth—White or Gray (G.), Black or Blackish (B.).		
DRYING.	FIXED.	ANIMAL.	DRYING.	FIXED.	ANIMAL.	DRYING.	FIXED.	ANIMAL.
Poppy (French).	Olive (superfine) Olive (crude).	Sheep-foot.	Linseed (North Europe), (B.Y.) Linseed (Bayonne), (B.Y.) White Poppy (India), (B.Y.) Hemp-seed (R.Y.). Nut (B.Y.). Castor (B.Y.).	Olive (ordinary). Olive (huile d'enfer), (R.Y.) Sweet Almond (faint Y.). Colza (faint Y.). Rape-seed (faint Y.) Pea-nut (gold Y.). Camline (faint Y.). Sesame (do.) Beech (do.) Cotton (do.)	Neat's-foot (Paris). B.Y.). Neat's-foot (Buenos Ayres), (gold Y.) Horse-foot (g'd Y.). Tallow (gold Y.). Sperm (B.Y.).	Sesame (greenish). Linseed (North Europe), (blackish). Linseed (Bayonne), (gray) Linseed (India), (blackish.) White Poppy (gray) Hemp-seed (green and greenish). Castor (black).	Olive (ordinary), (G.) Olive (huile d'enfer). Colza (B.). Rape-seed (B.). Pea-nut (G.). Camline (G.). Beech (B.). Cotton (gray).	Neat's-foot (blackish). Seal. Fish. Whale (greenish B.). (Sperm, G.). Cod (G.), (dirty green.) Ray (do.).
Browns—Reddish brown, Blackish brown.								
		Seal. Fish. Whale. Cod. Ray.						

PERNITRATE OF MERCURY.—Colors Given by the Salt alone.

White or Gray Emulsion, or no Coloration.			Yellow, Faint yellow, Gold yellow (G.Y.), Canary Yellow, Orange yellow (O.Y.), Straw yellow (S.Y.).			Greens—Greenish, Sea-green (S.G.), Bluish green.		
DRYING.	FIXED.	ANIMAL.	DRYING.	FIXED.	ANIMAL.	DRYING.	FIXED.	ANIMAL.
Poppy (French) White (slightly yellowish). White Poppy (slightly yellowish). Nut (no coloration). Castor (white).	Sweet Almond (grayish white). Sesame (white). Beech (no coloration).	Neat's-foot (Paris). Sheep-foot (W.) Tallow (no color). Sperm (no color).	Linseed (North Europe), (S.Y.) Linseed Bayonne), (S Y.) Linseed (India), (faint Y., with veins of dark Y.) Linseed(English), (faint Y.)	Olive (d'enfer), (canary Y.). Rape-seed (S Y.). Pea-nut (faint Y.). Camline (S.Y.). Sesame (O.Y.). Cotton (faint Y.).	Neat's-foot(R.Y.) Horse-foot (O.Y.) Whale (faint Y.). Seal (reddish Y.). Fish (G.Y.). Cod (S.Y.). Ray (faint Y.).	Linseed (English) Hemp-seed (greenish after agitation).	Olive (superfine), (greenish Y.) Olive (ordinary), (greenish Y.) Olive (crude), (S. G., and greenish Y.) Colza. Rape-seed (S.G.). Camline (faint G.).	

TABLE I.—COLOR REACTIONS OF THE OILS—*Continued.*

PERNITRATE OF MERCURY.

Colors given by Sulphuric Acid added after the action of the Salt of Mercury. Appearance of the Liquor covering the Precipitate.

Grays—Fleshy gray, Brownish gray (B.G.), Rose, Greenish gray (G.G.).			Yellows—Reddish yellow (R. Y.), Orange yellow.			Browns—Raw sienna (R S), Reddish Brown (R.B), Bright and Dark chocolate.			Disengagement of vapors of Nitrogen compounds. Sudden effervescence.		
DRYING.	FIXED.	ANIMAL.	DRYING.	FIXED.	ANIMAL.	DRYING.	FIXED.	ANIMAL.	DRYING.	FIXED.	ANIMAL.
Hemp-seed (G.G. by agitation).	Colza (dirty flesh color, then fleshy gray) Rape-seed (B.G.).	Sheep-foot (flesh-rose).	Linseed (N. Europe), (dirty Y. finally.) Linseed (Bayonne), (R.Y.) Linseed (India), (dirty Y.) Linseed (English), (deep Y.) White Poppy (R.Y.). Castor (canary Y. and Gold Y. at first).	Olive (ordinary), (R.Y.) Olive (d'enfer), (R. Y.) Sesame (green veins, then O.Y.).	Neat's-foot (Buenos Ayres), (R. Y. at first.) Horse-foot, (dirty B.Y. at first.)	Linseed (N Europe), (sepia R.B. then dirty Y.) Linseed Bayonne), (do.) Linseed (India), (R.B.) Poppy (French), (dark B.) Nut (light B., dark B., blackish B.). Castor (dark B.). Hemp-seed (dark R.B. without agitation).	Olive (superfine), (R.S. grayish). Olive (*lampante* R.B.). Sweet Almond (light chocolate). Colza (brownish rose, then bright B.). Pea-nut (chocolate). Camline (R. B., then chocolate). Beach (light R.B.). Cotton (light chocolate).	Neat's-foot (Paris). (chocolate B.) Neat's foot (B'nos Ayres). (R.B. and chocolate B.) Horse-foot (B. R. and chocolate). Tallow (light chocolate B.). Whale (dark chocolate B.) Sperm (light B. and black). Seal (br. bl.). Fish (br. bl.). Cod-liver (dark B). Ray-liver (sepia).	Linseed (N.). Linseed (Bayonne). Nut. Castor. The other drying-oils do not effervesce like the above.		Tallow. Seal.

95. **The Tables of Reactions** are referred to after first observing the indications furnished by organoleptic methods; the odor, taste, color, and consistency are characteristics that often assist in determining the method of adulteration. Several cases may be presented in the analysis of oils.

(1) Having a commercial oil the name of which is unknown (without label or label effaced, for example), to ascertain what it is.

(2) Knowing to what class an oil belongs, but not knowing its name, to ascertain it. For example, knowing of an oil that it is a drying, fixed, or animal oil.

(3) The name of an oil being certainly known, to ascertain whether it is pure or not.

These are three questions that the chemist, the purifier, or even the consumer, may at any time be called upon to decide —particularly the last.

First Case.—Knowing nothing of the oil, to ascertain its name.

First try the bisulphide calcium as directed in the instructions for preparing reagents. Suppose, for example, the oil gives a golden-yellow emulsion which retains its color. The oil tested may be linseed, nut, olive (fine or crude), sweet-almond, colza, rape-seed, sesame, camline, cotton, sheep-foot, tallow, or sperm. If in the reaction it does not produce effervescence and evolution of sulphuretted hydrogen, it cannot be tallow-oil. That is eliminated.

Try next a current of chlorine for a quarter of an hour. If it produces no black coloration, it is not sperm-oil.

Try chloride of zinc. This reagent gives a green, greenish, or bluish-green coloration; the table gives the linseeds of India, Bayonne, and North Europe, colza, camline, sweet-almond, refined olive, and the other grades of olive, cod, and ray oils.

The oil tested cannot be the lower grades of olive-oil, cod-liver, or ray-liver: bisulphide of calcium would have identified them. On the other hand, it is not rape-seed, sesame, cotton, English linseed, or sheep-foot, as the chloride of zinc would have detected them. We are thus limited to the linseeds of

India, North Europe, and Bayonne, colza, camline, sweet-almond, and the higher qualities of olive oil.

Try sulphuric acid. Assume it gives, for example, a dark reddish-brown and "dragon's-blood" color. Consulting the tables, it is seen that such effect indicates the linseed-oil of different countries, and a series of fixed and animal oils which had been eliminated by the preceding tests.

The oil is, therefore, linseed-oil, and it only remains to determine its origin.

Thus, without using the remaining tables, the name of the oil supposed to be offered for test is determined. By trying the reactions given by the other reagents indicated, the nature of the oil can be still more precisely ascertained. It is evident that another order of operations might have been followed, but it is best to commence with the bisulphide of calcium. This reagent divides the oils into two great groups; and we next proceed, using first simple then the more complicated tests.

Second Case.—Having given, for example, a fixed oil, to ascertain its name.

Try bisulphide of calcium. This reagent may give, for example, a golden-yellow emulsion, which retains its color. The oil can be neither olive of low quality, pea-nut, nor beech. It is useless to try chlorine here.

Pass on to chloride of zinc. We may obtain, for example, a greenish or bluish-green color; the oil cannot be a poor quality of olive-oil, sesame, rape-seed, or cotton-seed. There remain colza, olive, camline, or sweet-almond.

Test with sulphuric acid. This reagent gives, say, a reddish-yellow color. This eliminates colza and illuminating olive-oils, leaving camline, sweet almond, and fine olive.

Apply the fuming bichloride of tin. Perhaps a light brownish red may appear instantaneously, and with it a thick mass of faint or straw-yellow color. The first reaction eliminates sweet-almond and best olive; the second confirms the first.

The oil must then be camline. Special reactions given in the monography of this oil will clearly identify it.

The most unfavorable example has been selected to illustrate fully the use of these agents. Had a soap been obtained which did not retain its color, it would have limited the further investigation to only four oils. In such cases the labor is vastly reduced. A similar process would determine the name of any animal oil.

The bisulphide of calcium effects a primary division—three oils on one side and eight on the other. If the characteristics developed indicate one of the eight, the use of chloride will eliminate the fish-oils, leaving it to be decided whether it is neat's-foot or horse-foot oil.

Third Case.—To ascertain the purity of any oil indicated.

As an oil is only adulterated with oils less costly, it is usually not difficult to decide upon a limited range of possible adulteration. It is also evident that an oil can only be adulterated with a similar oil of inferior quality, or one possessing very similar properties. Thus an edible oil could not be adulterated with an oil of strong odor, as olive with fish, etc. It is true that a difference of price does not invariably limit adulteration, as the price varies in different seasons, and sometimes, even, from day to day. Thus colza is at one time quite costly, while linseed is cheap, and vice versâ. The adulteration of colza with linseed is therefore quite probable,—it is practised to a great extent,—but in other seasons the contrary is the case.

Suppose the purity of edible poppy-oil is to be tested? After having noted the organoleptic indications, test with the bisulphide of calcium. Suppose a soap obtained which retains its color? All the oils giving a soap which loses color are thus eliminated. Without further test, an examination of the tables will show that the three animal oils, sheep-foot, oleic acid, and sperm, are also easily eliminated, these oils having characteristic odor and taste. The linseed-oils also have odor, and are not edible. The adulteration could not be with fine olive-oil, for it is too costly. Illuminating olive-oil has a characteristic taste and odor, which throws that out. Cotton-seed oil, by its color and taste, and the oil of sweet almonds, by its price, are thrown out of the question. There remain nut, colza, rape-seed, sesame, camline, and poppy.

Try the chloride of zinc. Suppose a white or slightly yellowish mass be obtained? This reaction eliminates colza, rapeseed, and camline, leaving nut, sesame, and poppy.

Next use sulphuric acid, which may give a reddish-yellow color. As the nut-oil does *not* give this reaction, there remain sesame and poppy.

Trying the fuming bichloride of tin, it gives a faint-yellow coloration and a straw-yellow solidified mass. We still find these reactions to indicate sesame and poppy oils. It then becomes certain that the poppy oil is adulterated with sesame.

Try phosphoric acid. This gives, perhaps, a faint yellow—orange yellow. The detection is complete, since poppy-oil should give a white emulsion. Lastly, try Behrens' reagent, which will determine the presence of the oil of sesame with certainty.

These methods apply equally well to the greases as to the oils.

The reactions of the oils have been studied by many chemists, among whom are to be especially mentioned, besides Chateau, Calvert, Prescott, Gerhardt and Chancel.*

These reactions, for greater convenience, have been collected into a single large table for the author by Mr. L. S. Randolph, which table is here given.

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* **Prescott's Organic Analysis.—Précis d'Analyse Chemique Qualitative. MM. Gerhardt et Chancel.**

TABLE II.—PHYSICAL AND CHEMICAL PROPERTIES OF OILS AND COLOR REACTIONS.

[Compiled from CHATEAU, CALVERT, PRESCOTT, and other authors.]

KIND OF OIL.	S. G.	Congealing Point.	Natural Color.	Odor.	Taste.	Drying Qualities.	Calcium Bisulphide.
Almond	0.918	−20° C.	Clear straw-yellow; limpid.	None.	Bland sweetish.	Fixed.	Golden yellow; permanent.
Beech-nut	0.920	−18° C.	Yellowish.	Nearly inodorous.	Mild.	Fixed.	Golden yellow; not permanent.
Camline	0.925	−18° C.	Clear golden yellow.	Peculiar.	Peculiar.	Fixed.	Golden yellow; permanent.
Cod-liver	0.930	Below 14° F.	Clear yellow to red brown; acid reaction.	Fishy.	Fishy.	Animal.	Golden yellow; not permanent.
Castor	0.963	−15° C.	Sirupy; colorless.	Nauseating.	Mild; acrid after-taste.	Drying.	Golden yellow; not permanent.
Colza	0.914	− 6° C.	Limpid; clear yellowish.	....	....	Fixed.	Golden yellow; permanent.
Fish	......	... ...	....	....	....	Animal.	Golden yellow; not permanent.
Hemp-seed	0.926	−25° C.	Greenish when fresh, afterwards brownish yellow.	Unpleasant.	Insipid.	Drying.	Golden yellow; not permanent.
Lard	0.915	10° C. to 0° C.	Colorless, or nearly so.	Slight odor of lard.	....	Animal	Dark gray; effervesces, giving off H_2S.
Linseed	0.934	−27° C.	Gold yellow to brownish.	Strong.	Strong.	Drying.	Permanent.
Neat's-foot	......	Below 0° C.	Yellowish.	None.	Bland.	Animal.	Not permanent.
Olive (Refined).	0.916	5° C. to 2° C.	Greenish or yellowish; thick-flowing.	Slight pleasant or none.	Mild sweetish.	Fixed.	Permanent.
Olive (Ordinary salad)	0.917	+ 4° C.	Greenish yellow.	....	....	Fixed.	Not permanent.
Olive (Huile d'enfer)	0.917	+ 4° C.	Golden yellow, passing to brown.	Very odorous.	....	Fixed.	Not permanent.
Pea-nut	0.963	− 3° C.	Made hot it is yellow; almost colorless.	Almost odorless.	....	Fixed.	Not permanent.
Poppy-seed	0.924	−18° C.	Limpid; straw yellow.	Slightly pleasant odor.	Slightly pleasant taste.	Drying.	....
Rape-seed	0.914	− 6° C.	Clear yellowish.	Disagreeable.	Disagreeable.	Fixed.	Permanent.
Sesame	0.921	0° C.	Yellow.	Mild.	Mild.	Fixed.	Permanent.
Sperm	0.875	......	Limpid; orange yellow.	Fishy.	....	Animal.	....
Seal	......	......	....	....	....	Animal.	Not permanent.
Tallow, Mutton	......	37° C.	Hard white.	Decays rapidly.	....	Animal.	....
Tallow, Beef	......	37° C.	Hard white.	....	....	Animal.	....
Tallow, Veal	......	Melts betw'n fingers.	Soft white.	Decays rapidly.	....	Animal.	....
Walnut	0.925	−18° C.	Slightly greenish or yellowish; thick.	Nearly odorless.	Mild nutty.	Drying.	Permanent.
Whale	0.925	0° C.	Brownish.	Disagreeable.	Disagreeable.	Animal.	Not permanent.
Cotton-seed	0.925	1° C.	Yellow or brown; yellow to colorless.	....	Mild.	Fixed.	Permanent.

TABLE II.—PHYSICAL AND CHEMICAL PROPERTIES OF OILS AND COLOR REACTIONS—*Continued.*

KIND OF OIL.	Chloride of Zinc.	Sulphuric Acid.	Fuming Bichloride of Tin.	Thickened Mass, from $SnCl_2$.	Cold Phosphoric Acid.
Almond.........	White mass, slightly yellow or no color.	Yellow.	No color.	Canary yellow.	Discolored.
Beech-nut.......	Flesh rose.	Reddish brown.	Reddish yellow.	Reddish yellow.	White.
Camline.........	Yellowish green to bluish green.	Reddish yellow.	Brownish yellow to reddish brown.	Faint yellow.	Discolored.
Cod-liver	Greenish yellow to bluish yellow.	Violet red, crimson violet, then darkbrown	Green to greenish blue.	....	Reddish yellow.
Castor	Yellowish rose.	Bright yellow, then reddish yellow.	No color to golden yellow.	Faint yellow.	White.
Colza	Greenish yellow to bluish yellow.	Green veins or greenish color.	Green to greenish blue.	Yellow to brown.	Greenish.
Fish	Yellow to brown.	Brownish black.	Deep reddish brown.	Deep sepia.	Reddish yellow.
Hemp-seed......	....	Green veins or green color.	Green.	Dark green.	Dark green.
Lard	Reddish-yellow emulsion.	Red brown.	Reddish.	Does not thicken; brown red.	Clear yellow.
Linseed...	Greenish yellow; bluish yellow.	Dark brown; brownish red.	Bluish green.	Brownish.	Straw-yellow.
Neat's-foot... ..	White mass, slightly yellow or no color.	Yellow, then orange yellow.	Reddish yellow.	Orange yellow.	Yellow.
Olive .... (Refined).	Greenish yellow to bluish green.	Yellow.	Yellow (?)	....	Greenish.
Olive .... (Ordinary salad)	Greenish yellow to bluish green.	Yellow.	Yellow.	Orange yellow.	Greenish.
Olive .... (Huile d'enfer)	Greenish yellow to bluish green.	Yellow, then reddish yellow.	Reddish yellow.	Reddish yellow.	Greenish.
Pea-nut	Yellow to brown.	Dark brown to reddish brown	Distinct brown.	Brownish red.	Straw-yellow.
Poppy-seed	White mass or no color.	Bright yellow, then orange yellow.	Reddish yellow.	Yellow.	White.
Rape-seed	Yellow to brown.	Green veins or greenish color.	Greenish.	Dirty green.	White.
Sesame..........	No color or white mass.	Yellow to reddish yellow.	Faint yellow.	Yellow.	Straw-yellow and orange yellow.
Sperm	No color or white mass.	Brownish red.	Purplish; reddish brown.	Orange yellow.	Straw-yellow.
Seal.............	Reddish brown.	Dark brown.	Brownish.	....	Distinct brown red.
Tallow, Mutton.	No color.	Yellowish.	Canary yellow; H_2SO_4 deepens the tint.	....	No color.
Tallow, Beef ..	No color.	Pale yellow; when stirred a reddish yellow.	Deep yellow.	Stringy yellow mass.	....
Tallow, Veal....	....	Canary yellow; slightly orange.	Canary yellow; H_2SO_4 deepens the tint.	....	....
Walnut	White mass, slightly yellow or no color.	Reddish brown.	Reddish yellow.	....	White.
Whale...........	Yellowish brown	Brownish red.	Orange yellow.	Clear mahogony.	Straw yellow, then orange yellow.
Cotton-seed.....	Dark brown.	Reddish brown.	Orange yellow.	Yellowish brown.	Golden yellow.

TABLE II.—PHYSICAL AND CHEMICAL PROPERTIES OF OILS AND COLOR REACTIONS—*Continued.*

KIND OF OIL.	Hot Phosphoric Acid.	Pernitrate of Mercury.	Addition of Sulphuric Acid.	Potash.	Ammonia.
Almond.........	Faint yellow.	Grayish white.	Light chocolate.	Greasy yellow soap	Greasy yellow soap.
Beech-nut.......	Faint yellow.	No coloration.	Light reddish brown.	Thick white emulsion.	White emulsion, when hot.
Camline.........	Faint yellow.	Straw yellow.	Reddish brown, then chocolate.	....	....
Cod-liver.......	Dirty green	Straw yellow.	Dark brown.	....	....
Castor....	Bright yellow.	White emulsion.	Canary yellow; golden yellow at first.	Flocculent white soap.	White emulsion.
Colza........ ..	Brown.	Greenish.	Dirty flesh color.	....	....
Fish	Blackish.	Golden yellow.	Brownish black.	....	....
Hemp-seed......	Green or greenish.	Greenish after stirring.	Dark reddish-brown.	....	Greenish-yellow soap, very thick.
Lard............	Golden yellow; effervesces	No color.	Violent effervescence; chocolate brown.	Reddish yellow soap; very thick.	White soap, very thick; gelatinous when heated.
Linseed.........	Bright yellow.	Greenish.	Reddish brown.	Pale yellow emulsion.	Clear golden-yellow emulsion.
Neat's-foot......	Bright yellow.	Reddish yellow.	Reddish yellow.	Difficult to saponify	Thick white emulsion.
Olive.......... (Refined).	Reddish yellow.	Golden yellow.	Raw sienna.	....	....
Olive...... .... (Ordinary salad)	Gray.......	Greenish yellow.	Reddish yellow.	Thick yellowish-white soap.	Very thick, gelatinous soap; very white.
Olive.......... (Huile d'enfer)	Gray.	....	Reddish yellow.	Pale-yellow soap, like a precipitate	Clear-yellow soap, becoming yellowish white.
Pea-nut	Gray	Faint yellow.	Chocolate.	Pale-yellowish soap.	Thick soap; slightly yellowish.
Poppy-seed......	No color.	Slightly yellowish.	Dark brown.	Greasy emulsion; not homogeneous.	Yellow emulsion.
Rape-seed	Brown.	Straw-yellow.	Brownish gray.	Deep yellow, homogeneous soap.	Deep-yellow emulsion, becoming homogeneous and pale clear yellow.
Sesame...... ...	Faint yellow.	White.	Orange-yellow; green veins.	....	....
Sperm	Bright yellow.	No color.	Light brown and black.	Yellow emulsion, slightly reddish.	Pale-yellow emulsion.
Seal............	Blackish.	Reddish yellow.	Brownish black.	Reddish-yellow soap.	Thick reddish-yellow soap.
Tallow, Mutton.	Greenish yellow.	Pale rose.	Slight chocolate.	....	....
Tallow, Beef....	Greenish yellow.	Rosy when cold, disappears when hot.	White precipitate; brownish violet.	....	....
Tallow, Veal....	....	No color at first, afterwards flesh-color.	White precipitate; sienna passing to sepia.	....	....
Walnut.........	Bright yellow.	No color.	Sudden effervescence.	....	....
Whale	Reddish brown.	Faint yellow.	Dark chocolate brown.	Orange emulsion, changing to thick soap.	Yellow emulsion, passing to yellow-white.
Cotton-seed.....	Faint yellow.	Faint yellow.	Light chocolate.	Homogeneous reddish-yellow soap, with green veins.	....

To detect acid, dissolve a small piece of sodium carbonate in an equal volume of water, and introduce the solution with the oil to be tested into a flask, and agitate thoroughly. The quantity of precipitate will be a gauge of the amount of acid present.

The application of the senses of taste and smell, in the testing of lubricants, to be satisfactorily useful demands great familiarity with, and experience in the use of oils, and can be practised with satisfactory results, usually, only by experts. Some oils, however, are so characteristic in taste and odor that a novice may readily recognize them. It is always best to compare the suspected oil with a sample of known purity. The characteristic odor of an oil can be brought out more strongly by warming it. The taste, odor, and "feel" of the oil are sometimes considerably modified by the locality whence it is obtained, by the season during which it is prepared, and by the method of manufacture.

METHODS IN DETAIL are given as follows by M. A. Remont:*

Qualitative Analysis should be preceded by an examination of the organoleptic properties of the oil, the manner in which it behaves under the influence of heat, and of its specific gravity. If the specific gravity of the sample is below 0.900, it contains a mineral oil; if from 0.900 to 0.975, it may contain the most complex mixtures; but if it is above 0.975, it is certainly an oil of resin.

Begin by treating the sample with carbon-disulphide, freshly prepared, which gives a clear solution with all oils. If oleic acid or a fatty oil has been mixed with alkali to raise its specific gravity by the formation of soap, there will be a precipitate. In such case the liquid is filtered, and the residue washed with carbon disulphide. It may be shown to be soap by its solubility in water, its alkalinity, and the turbidity more or less marked, which is caused by an acid poured into the solution.

The filtrate is next freed from the carbon-disulphide by distillation: 1 c.c. of the residue is mixed with 4 c.c. of alco-

* *Bulletin de la Société chimique de Paris.—Chemical News*, 1880.

hot at 85°. If solution takes place, fatty acids are present, pure or mixed, and an excess of alcohol is gradually added If after having poured in 50 c.c. the liquid is limpid or very slightly cloudy, which cloudiness disappears on adding a drop of hydrochloric acid, the sample consists of oleic acid, pure or mixed with resin. If the specific gravity does not exceed 0.905 at 15°, the sample is pure oleic acid. If the specific gravity is higher, it contains resin. By way of confirmation it may be examined with the polariscope, either alone or dissolved in carbon-disulphide; and if there is a deviation the presence of a resinous mixture is indicated.

If persistent cloudiness is observed in the alcoholic solution the fatty acids contain an oil sparingly soluble in this solvent, and in greater quantity as the cloud appears earlier. This process renders it possible to detect 2 or 3 per cent. of mineral oil, of resin, or fatty oil in the oleic acid known as oleine. The turbidity produced in the alcoholic liquid resolves itself after a time into little oily drops, which line the sides of the vessel and which can by jarring be made to fall to the bottom of the tube. The volume of this residue shows approximately the proportion of insoluble matter.

In the usual case 4 parts of alcohol do not completely dissolve 1 part of oil. A larger quantity of the latter is then taken and agitated with an equal volume of alcohol. After settling, the alcoholic solution is decanted, and evaporated in a capsule. The nature and the quantity of the residue give a clew to the nature of the mixture.

Next submit the oil to the action of caustic soda, employing the method of M. Dalican for the analysis of tallows. In a capsule of porcelain, or preferably of enamelled cast-iron, there are weighed about 20 grammes of oil, and heated to 100° to 110°. There is then poured in a mixture of 15 c.c. soda-lye at 36° B., and 10 c.c. of alcohol; the mixture is stirred and heated until the alcohol and the greater part of the water have disappeared. Then 150 c.c. of distilled water are added, and the boiling is kept up for half an hour, when three cases may occur:

(1) The oil under the influence of the alkali is merely

emulsified, and on the addition of water it separates distinctly; this indicates either a mineral oil, a resin-oil, or a mixture of the two. The aqueous solution is decanted off, and is mixed with sulphuric acid. If there is no precipitation, or if but slight cloudiness is produced, the sample is a pure mineral oil. If there is a considerable precipitate which collects in brown viscid drops, giving off a strong odor of resin, and soluble in an excess of alcohol, we have a resin-oil, pure or mixed. The oil is examined with the polariscope, and if it acts upon polarized light this is a confirmation of the presence of resin-oil. If the specific gravity is below 0.960, there is some mineral oil present. A test may be made by distillation if one of the oils is not in too small proportion. The distillation should be fractional as far as possible, and conducted slowly. As the resin-oils boil, as a rule, at lower points than the heavy mineral oils, it follows that, in place of having specific gravities which increase with the boiling-points, as happens with the heavy mineral oils or pure resin-oils, there are observed with their mixtures very abrupt transitions. The sample ought to be tested with tannic chloride, and if the violet coloration is not very distinct, the same reagent should be applied to the first products of distillation, since the colorable product contained in the resin-oils is there chiefly met with.

(2) There is formed by the action of caustic soda a paste-like mass of soap, which on treatment with water and boiling for some time gives a clear liquid. It is diluted with cold water and then supersaturated with acid. The fatty acids liberated collect on the surface after decantation of the water, and if exposed to cold crystallize. A small portion is melted in a tube at a low temperature, and 4 parts of alcohol at 85° are added first, and later an excess. Here two cases are possible:

A. If no precipitation takes place it is because the fatty acids are pure, which shows that the oil examined is a pure fatty oil, or, which rarely happens, mixed with resin. The specific gravity of the fatty acids may here give good indications, but it cannot be taken at ordinary temperatures, at which fatty acids are solid. They must be melted, and the specific gravity taken at a definite temperature. M. Baudouin

has given a table of the specific gravities of the fatty acids of certain oils taken at 30° C. Except for linseed-oil, which marks 0.910, the fatty oils have specific gravities ranging from 0.892 to 0.900. To reduce the specific gravities of the fatty oils examined to the temperature of 30°, deduct from the density found, calculated on the litre, as many times 0.64 gramme as there are degrees below, or, if the temperature is higher, to add to the density found as many times 0.64 gramme as there are degrees above. If the specific gravity indicates that the neutral oil contains resin, an attempt may be made to separate it, in part at least, rapidly by agitating 5 or 6 c.c. of the original oil with an equal volume of alcohol, decanting after settling, and evaporating in a capsule. There is thus obtained a solid or semi-fluid residue in case of resin. Further examination is then made with the polariscope.

B. The fatty acids derived from the decomposition of the soap give a precipitate if treated with an excess of alcohol. If it is not, redissolve by 1 gramme of hydrochloric acid, and if after some time it is resolved into oily drops, it is mineral oil or resin-oil. A fatty oil containing 10 to 15 per cent. of one of these oils is completely saponified, and yields with boiling water, not an emulsion, but a soap completely soluble. The turbidity should yield oily drops, for there are certain fatty acids—those, among others, of the oil of the ground-nut or pea-nut (*arachis*)—which are soluble in a small proportion of alcohol at 85°, but an excess of alcohol precipitates a sparingly soluble portion of arachidic acid in small flocks. These flocks may be collected on a filter, and examined as to their complete solubility in alkalies. If their melting-point is near 73° they may be attributed to pea-nut oil.

(3) Or, lastly, the oil on treatment with soda may give a paste more or less firm, which, if placed in boiling water for half an hour, allows oily drops to rise to the surface, which are due to a mineral oil or a resin-oil. After settling for some minutes, a part of the supernatant liquid is decanted and mixed with an excess of a saturated solution of common salt. There is produced a precipitate of soap, which is filtered off on cooling. The filtrate is supersaturated with an acid. If

there is produced a slight turbidity, and if the liquid, which was almost colorless when alkaline, gives off an odor of fatty matters, we have a neutral oil mixed with a non-saponifiable oil. If, on the contrary, the solution was highly colored after filtration, and gives, when acidified, a flocculent precipitate of a resinous odor, the sample is a mixture containing resin. In these two cases the components of the mixture may be recognized by means of the operations indicated above.

Quantitative Analysis.—If it is desired to know the elements attacked by alkalies, the following method is to be followed: If the sample has yielded bodies insoluble in carbon-disulphide, it is separated, and the operation is confined to the residue of the distillation. Let it be assumed that the composition of the residue is as complex as possible, containing fatty oils, mineral oils, resin-oils, and solid resin.

The mixture is saponified. Into a flask closed by a stopper, through which passes a long tube, are introduced 20 grammes of the oil, and a mixture of 15 c.c. of soda at 36° B., and 15 c.c. alcohol at 90 to 95 per cent. The flask is then set upon the water-bath for half an hour, and is often shaken. At the end of this time the whole is poured into a funnel fitted with a tap and previously warmed, and which is left in a stove at 50° to 60° until a complete separation of the non-saponifiable oil from the alkaline liquid has taken place. The latter is then decanted into a porcelain capsule, and in its stead is poured 15 c.c. of boiling water, which has served to rinse the flask. It is shaken well so as to wash the non-saponifiable matter, and decanted anew after settling. Finally it is washed a third time with boiling water. The oil in the funnel is received in capsule and weighed. What adheres to the sides is washed with a little ether, and the solution is received in another capsule, which is exposed to the air till the ether has principally disappeared. It is then gently heated to expel the rest, and is weighed.

The alkaline liquid is kept boiling for some time to expel the alcohol, and after cooling it is mixed with an equal volume of a saturated solution of common salt freed from magnesia by being boiled for a few moments with caustic soda and then

filtered. In this manner the soap is precipitated in firm clots, carrying with it the last portion of non-saponifiable matter. The saline solution after settling is decanted by means of a pipette, and neutralized with an acid. If a notable turbidity is produced which collects in flocks, it is due to the presence of resin. The flocks are collected, dried, and weighed. The clots of soap are thrown upon a filter, washed twice with salt water, the last traces of which are removed by pressing the mass between sheets of blotting-paper. The soap is then placed in a glass beaker, moistened with about 100 c.c. of carbon-disulphide recently rectified, stoppered, gently shaken at intervals, so as not to break the clots, three or four times, and left to settle. After an hour or two the carbon-disulphide, which is colored yellow by the dissolved oil, separates in the lower part of the beaker. It is decanted by means of a pipette, and in its place is added a fresh portion of the solvent. It is shaken, left to settle, decanted, and so on, till the carbon-sulphide runs off almost colorless. The whole is then thrown upon a filter and washed for the last time. A portion of this last washing, if evaporated upon a watch-glass, should leave an insignificant residue.

The soap on the filter is exposed to the air till the carbon-disulphide with which it is saturated has escaped. As for the carbon-disulphide solution, it is distilled gently on the water-bath. The last portions of the solvent are expelled by blowing air into the flask while placed in boiling water. When cold it is weighed.

The last portion of the non-saponifiable matter thus obtained should have the same appearance as the first portion. If it is less fluid it still contains a portion of soap. In this case it is again taken up in carbon-disulphide, at a gentle heat, in presence of a few drops of water, to hydrate the soap, which without this addition would again be partially dissolved. It is then filtered, and the washed soap is added to the principal mass.

The non-saponifiable oil may consist of mineral oil, resin-oil, or a mixture of both. The means of detection have been given, but a satisfactory process for their separation is needed.

The soap insoluble in carbon-sulphide, which lies on the filter, contains resin and fatty acids combined with soda.

The separation of these substances presents many difficulties. Several methods have been published, but none of them gives satisfactory results. That of M. Jean consists in exhausting the barium-soap with ether, which should dissolve the resinate and leave the soaps of the fatty acids untouched. It is difficult to avoid the partial solution of the barium-oleate. Substituting for the ether boiling alcohol at 85 per cent., it dissolves much less of the oleate, but still takes up too much.

As far as possible the soap is separated from the filter and placed in a capsule. The filter is put back in the funnel and filled with boiling water, The solution is effected slowly, and it filters by degrees; it is received in the capsule where the detached portion has been already placed.

The solution of soap after cooling is mixed with caustic soda until precipitation ceases, and is left to settle. All the soap of the fatty acids is deposited, carrying down with it the chief portion of the resinate, a part of which, however, remains in solution and colors the liquid strongly. The whole is filtered, the filtrate accurately neutralized with sulphuric acid; the flocks of resin deposited are received upon a filter, which is weighed anew after washing in water and drying at a low temperature. The soap is redissolved in a little lukewarm water and an excess of barium-chloride is poured into the solution with agitation. The clots of barytic soap are drained in a filter-pump, replaced in the capsule in which the precipitation has been effected, and thoroughly dried in the water-bath or the stove. The mass is then powdered, and treated with 50 or 60 c.c. of alcohol at 85 per cent., which is kept near the boiling-point, working it up with a pestle. It is left to settle for a few moments, and the supernatant alcoholic liquid is then decanted into a vial. 20 to 25 c.c. of alcohol are again poured upon the residue, let boil, decanted after settling, and so on till a portion of the alkali which has been used leaves on evaporation scarcely any residue, which happens generally after 120 c.c. of alcohol have been used.

The alcoholic liquids are mixed and distilled till there re-

mains only about 50 c.c. Hydrochloric acid is added to decompose the resinate, and the resin, set at liberty, floats in the liquids. On cooling, it collects in a solid mass at the bottom of the vessel. It is thrown into a capsule, melted under water, and weighed after desiccation on the water-bath.

The residue insoluble in alcohol is treated in a similar manner to obtain the fatty acids.

Olive-oil is sometimes tested for purity by simply applying heat.

This test is very simple, and can be performed by any one possessing a good chemical thermometer. About a teaspoonful of oil is put in a test-tube, and a thermometer suspended in the oil, which is now to be heated to 250° C. (472° F.). For a comparison, a second test-tube of pure oil may be treated in like manner. Pure olive-oil, when heated, grows rather lighter in color, but most other oils, like cotton-seed, pea-nut oil, etc., grow darker. The latter, also, evolve a penetrating and disagreeable odor, but olive-oil has a pleasant smell not unlike strawberries. This test, devised by Merz, is considered worthy of a trial.

When mixed with cotton-seed oil, the following method is proposed by Dr. Nickels:*

Pure olive, or "Gallipoli," oil, as examined by a Browning "direct vision" or pocket spectroscope, presents a deep shadowing, or cutting-out, of the blue and violet ray, with a fine, almost indistinct, line in the green, and a strong deep band in the red.

Refined cotton-seed oil similarly examined presents exactly the same appearance, but as regards the blue and violet ray only, the green and red being continuous.

If we take as a standard a given stratum of pure olive or Gallipoli oil in a test-tube, and a similar stratum or thickness of the standard oil in admixture with cotton-seed, there is no discernible difference as regards the shadowing in the blue and violet ray, but an almost entire fading out of the delicate line in the green, and a considerable diminution in the depth and

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* *Chemical News.*

intensity of the strong band in the red, consequent upon "dilution" or "thinning down." With 50 per cent. in admixture, the loss in intensity is considerable; with 25 per cent. the variation is marked and discernible.

A suspected sample compared with and differing thus from the standard, and in the absence of any direct chemical evidence as to the nature of the oil in admixture, might fairly fall within the range of strong presumptive evidence pointing towards "cotton-seed" oil as the probable dilutant.

Pure olive-oil is exceedingly difficult to secure with certainty when purchasing in large quantity, as it is often greatly adulterated at the point of production. It is usually very difficult to distinguish the several vegetable oils in any mixture of them.

96. **Alterations of Composition** occur in the animal and vegetable oils, with exposure to air and light and with advancing age, which may sometimes cause some uncertainty in the chemical work already described. These changes are usually in the direction of those modifications which lead to the production of resins. The oils become darker, more viscous, less susceptible to the action of reagents, and, if time be allowed, finally become "gummed," and completely altered into resins of various degrees of solidity. Such changes are so plainly observable, however, that no special tests are necessary to indicate their commencement or their progress. The mineral oils are not subject to such alterations to any serious extent, unless very long exposed to the action of oxygen and of light, in which case the absorption of the gas and its conversion into ozone, with some loss of lubricating power and greater reduction of its value as an illuminant, become matters of some importance.

97. **The Action of Oils on Metals** is sometimes important. Copper and lead, and other soluble metals, are sometimes found in oils; and Dr. Stevenson McAdam found that the second of the two metals above named may go into solution to such an extent as to injure the quality of the oil as an illuminant very seriously. In such cases the metal is usually absorbed by the oil from the metallic walls of the vessels in which it is stored.

Dr. McAdam found this to occur to such an extent as to clog up the wick and ultimately diminish its capillary attraction so much that the light was extinguished. The wicks when charred left a fine net-work of lead. The action of the oil on tin, copper, and iron was slight, and its illuminating properties were not much diminished. Zinc, however, was quickly attacked, and the oil was as seriously affected as by lead. While the vessels for the retention of paraffine-oil may be safely constructed of or be lined with tin, copper, or iron, it would evidently be preferable to use tanks lined with enamel for storing the oil.

Detection of Copper and Lead.—To detect the presence of copper, mix a small portion of the oil with twice its weight of nitric acid in a test-tube, and shake well; then, separating the acid from the oil, add ammonia to the former: if copper is present, the reaction will give a blue color by the formation of an ammoniacal solution of that metal.

To detect lead, add to a portion of the oil, contained in a test-tube, a small quantity of sulphuric acid, of carbonate of soda, or of caustic soda: if lead is present the solution will become white, and will yield a precipitate of similar color. To insure certainty, add to the solution caustic soda until the acid, if used, is neutralized, or add acid, if soda has been used, and a few drops of sulphur-solution, the presence of lead will be indicated by a dark-brown precipitate. With bichromate of potassium or the iodide of potassium, a yellow precipitate is found.

Dr. Watson concludes,* in regard to this action—

(1) That of the oils used, viz., linseed, olive, colza, almond, seal, sperm, castor, neat's-foot, sesame, and paraffine, the samples of paraffine and castor oils had the least action, and that sperm and seal oils were next in order of inaction.

(2) That the appearances of the paraffine and the copper were not changed after 77 days' exposure.

(3) That different oils produce compounds with copper varying in color, or in depth of color, and consequently rendering

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* Paper read in the Chemical Section of the British Association, Plymouth Meeting, 1879.

comparative determinations of their action on that metal from mere observations of their appearances impossible.

He later * experimented further, with the following results, noted, after one day's exposure, with iron:

(1) *Neat's-foot.*—Considerable brown irregular deposit on metal. The oil slightly more brown than when first exposed.

(2) *Colza.*—A slight brown substance suspended in the oil, which is now of a reddish-brown color. A few irregular markings on the metal.

(3) *Sperm.*—A slight brown deposit, with irregular markings on the metal. Oil of a dark-brown color.

(4) *Lard.*—Reddish brown, with slight brown deposit on metal.

(5) *Olive.*—Clear and bleached by exposure to the light and air. The appearance of metal same as when first immersed.

(6) *Seal.*—A few irregular markings on metal. The oil free from deposit, but of a bright clear red color.

(7) *Linseed.*—Bright deep yellow. No deposit or marks on metal.

(8) *Almond.*—Metal bright. Oil bleached and free from deposit.

(9) *Castor.*—Oil considerably more colored (brown) than when first exposed. Metal bright.

(10) *Paraffine.*—Oil bright yellow, and contains a little brown deposit. The upper surface of the metal on being removed is found to have a resinous deposit on it.

The tendency of an oil to act on metals varies with the proportion of free acid and kind of oil, and also with the nature of the metal. Nearly all fatty oils act more rapidly on copper than on iron. The following table shows results obtained by Watson with iron exposed to the action of oils for twenty-four hours and with copper after ten days' exposure:

* Swansea Meeting, British Association, 1880.

ACTION OF OILS ON METALS.

OILS.	Iron dissolved in 24 days.	Copper dissolved in 10 days.
Almond	.0040 grain.	.1030 grain.
Castor	.0048 "	....
Colza	.0800 "	.0170 grain.
Lard	.0250 "	....
Linseed	.0050 "	.3000 grain.
Neat's foot	.0875 "	.1100 "
Olive	.0062 "	.2200 "
Paraffine	.0045 "	.0015 "
Seal	.0050 "	.0485 "
Sperm	.0460 "	.0030 "

There is evidently no relation between the action of an oil on copper and the action of the same oil on iron: in several instances, those oils which act largely on iron act slightly on copper, while those which act largely on copper act little on iron. The total amount of action of the same oil (with the exception of paraffine and probably other mineral oils) is greater on copper than on iron.

98. Impurities in Mineral Oils consist, usually, of the gritty and earthy substances which rise in the well with the oil, and of the "still-bottom" impurities which are produced in the process of refining. The presence of the latter in other oils is the best possible evidence of the admixture of the mineral oils. They may be detected by dropping a little of the suspected oil on white blotting-paper, which absorbs the oil, leaving the impurities visible as black specks on its surface. The abnormally low temperature at which the oil vaporizes in contact with these particles is also a means of detecting their presence. The presence of mineral oils in other oils may sometimes be readily detected by holding a bottle of the oil to be examined up to the light, and shaking it well, when the appearance of fluorescence in the bubbles of air so formed is an unmistakable sign of the presence of petroleum.

The following method of estimating the proportions of mineral and other oils in the common mixtures is given by Mr. C. C. Hall,* as based on a method suggested by Sir William Thomson and Mr. A. H. Allen.

* Trans. Am. Inst. Mining Engineers, 1882.

Four to five grains of the oil under examination are weighed out into a porcelain capsule of 75 c.c. capacity. Thirty c.c. of a ten-per-cent solution of potassium-hydrate are added, and the capsule, covered with a watch-glass, is placed in a water-bath heated to about 93° C. The mixture of oil and alkali should be stirred frequently, and after three quarters of an hour it is boiled with stirring, to secure complete saponification of all vegetable or animal oil. After boiling some time, a thick scum of soap forms on the surface; a little bicarbonate of soda is then added to convert the excess of caustic alkali into carbonate. When the contents of the capsule have become pasty, an equal bulk of fine clean sand is stirred in, which makes the soap granular, and facilitates the removal of the last traces of alcohol. The capsule is heated for two hours more on the water-bath. After cooling, the contents are transferred to a short-necked funnel, having a thin plug of asbestos, and washed with petroleum-ether, or other light petroleum-spirit. The ether dissolves out the mineral oil from the soap, and is collected in a quarter-litre flask having a short neck. Care must be taken to effect a complete removal of the oil. This can be tested by letting a drop of the ether, as it comes through, fall on a piece of tissue-paper. If no greasy stain is left after the ether evaporates, the solution may be considered complete.

Most of the ether is removed from the oil by distillation, and can be saved. The heat of the water-bath is sufficient to boil it, and the fumes may be condensed by passing them into a condenser. The oil is now transferred to a weighed 50-c.c. flask, which has a hole blown in its side; and dry, warm air is forced into the flask through its neck in order to remove the last traces of the ether. The flask should not be heated above the point where it can be borne in the hand: if this precaution is heeded, there is no danger that any of the oil will be volatilized. The passage of the air should be continued until the flask and oil are constant in weight.

Sperm-oil cannot be separated from mineral oil by this method, owing to the impossibility of completely saponifying it.

To determine the proportion of earthy matter in the gummy masses sometimes found in steam-engines in which organic oils and steam carrying dirty water from the boilers have come in contact:

Weigh out any convenient amount of the deposit; wash well with benzine until it ceases losing weight and all oily matter is removed; dry, and weigh again.

The proportion of mineral matter usually ranges from 85 to 95 per cent.

99. **The Density of Oil** is the first of its physical characteristics noted by the inspector in the attempt to determine its character. It is, perhaps, the simplest and easiest method of identifying a standard oil, although by no means a certain one. This may be done by carefully weighing an exactly measured volume of the lubricant, and comparing its weight with the standard volume of a standard substance, or by the use of the "densimeter," or oleometer. This little instrument, generally known as the hydrometer, takes its specific name from the application for which it has been designed; as, for example, lactometer when used to determine the density of milk, and alcoholometer when used to measure that of alcohol. It consists (Fig. 29) of a glass or metal cylinder, usually of an inch (2.4 cm.) or less diameter, and several diameters in length, carrying at the lower end a bulb loaded with shot, or mercury, or other heavy substance, and on the upper end a cylindrical stem graduated in such a manner as may be best suited to the work for which it is intended. A cylindrical tank or jar, with attached thermometer, is nearly filled with the liquid to be examined.

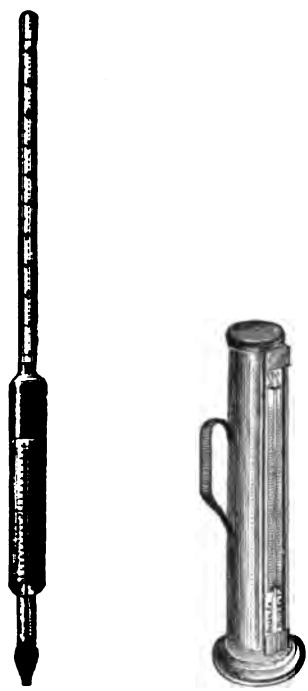

FIG. 29.—OLEOMETER AND JAR.

Placing the instrument in the liquid, it floats upright, with the loaded end downward, and sinks to such a depth that the figure on the stem reads the density or the specific gravity (the terms are not precisely synonymous) of the liquid.

The liquid must usually be tested at standard temperature, —say, 60° F. (15° C.),—as its density is considerably affected by heat or cold. The hydrometer has a thermometer attached to the lower end. This is intended to assist in making corrections for a temperature above or below 60°. When the thermometer indicates a temperature above 60°, which is shown by the figure on the right side, the corresponding number opposite must be added to the indications on the scale above. If the thermometer stands below 60°, the corresponding number opposite must be deducted.

100. Specific Gravities and Baume's Scale, often used in this work, are not proportional, the latter scale being conventional. The specific gravity of a substance is proportional to its density, and is the ratio of the weight of a given volume of the substance to that of an equal volume of water, both being usually taken at the temperature of maximum density of the latter. For liquids lighter than water, $\frac{140}{130 + \text{Baumé}} =$ specific gravity, and $\frac{140}{\text{sp. gr.}} - 130 = B°$, the reading of Baumé.

As illustrating the use of the instrument, assume it to be used for obtaining the gravity of an oil—sperm, for example: finding it to be 0.8750, or 30° Baumé, it would be at once concluded to be impure; because sperm should give about 0.8810 or 0.8815, corresponding to 29° B. Oils often differ considerably in density, although nominally the same.

The following table gives the specific gravities and Baumé's "degrees" for liquids heavier than water, as obtained by various authorities.* It is evident that the determination of the specific gravity, or the use of a carefully standardized Baumé scale, only can give satisfactory figures.

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* Chandler and Wiechmann.

BAUMÉ'S SCALE AND SPECIFIC GRAVITIES.

Degrees Baumé.	Delezennes, 12.5° C. Mod. = 139.97. before 1848.	Ziurek, 12.5° C. Mod. = 143.64. 1863.	French Codex, Holland, 12.5° C. Mod. = 144. 1805.	H. A. Mott, Jr., 17.5° C. Mod. = 144. 1877.	Bourgougnon, 15° C. Mod. = 144.32. 1878.	Morozeau, 12.5° C. Mod. = 144.38. 1830.	Custom in France, Mod. = 144.38. 1872.	J. Kolb, 15° C. Mod. = 144.38. 1872.	H. Pemberton, Mod. = 145. 1851.	Mfg. Chem. Ass'n, U.S. A. H. Elliott, 1877. 15.5° C. Mod. = 145.04.	Schober & Pecher, 15.5° C. Mod. = 145.13. 1828.	Huss, Edinb. Disp., Mod. = 145.40. 1830.	Chem. Kalend., Berlin. 12.15° C. Mod. = 146.98. 1881.	Francœur, 12.5° C. Mod. = 152.05. before 1848.
0	1.0000	1.000	1.000	1.0000	1.0000	1.000	1.000	1.000	1.0000	1.000	1.0000	1.0000	1.000	1.000
1	1.0072	1.007	1.007	1.0070	1.0069	1.008	.....	1.007	1.0069	1.005	1.0069	1.0070	1.007	1.007
2	1.0145	1.014	1.014	1.0141	1.0140	1.015	.....	1.014	1.0139	1.011	1.0139	1.0141	1.014	1.013
3	1.0219	1.022	1.022	1.0213	1.0212	1.022	.....	1.022	1.0211	1.023	1.0211	1.0213	1.020	1.020
4	1.0294	1.029	1.029	1.0286	1.0285	1.029	.....	1.029	1.0283	1.029	1.0283	1.0286	1.028	1.027
5	1.0370	1.036	1.036	1.0360	1.0358	1.036	1.023	1.037	1.0357	1.036	1.0356	1.0360	1.034	1.034
6	1.0448	1.044	1.044	1.0435	1.0433	1.043	.....	1.045	1.0431	1.043	1.0431	1.0435	1.041	1.041
7	1.0526	1.052	1.052	1.0511	1.0509	1.051	.....	1.052	1.0507	1.050	1.0506	1.0511	1.049	1.048
8	1.0606	1.060	1.060	1.0588	1.0586	1.059	1.055	1.060	1.0583	1.057	1.0583	1.0588	1.057	1.056
9	1.0687	1.067	1.067	1.0667	1.0665	1.067	.....	1.067	1.0661	1.064	1.0661	1.0666	1.064	1.063
10	1.0769	1.075	1.075	1.0746	1.0744	1.075	1.076	1.075	1.0740	1.071	1.0740	1.0745	1.072	1.070
11	1.0853	1.083	1.083	1.0827	1.0825	1.083	.....	1.083	1.0820	1.086	1.0820	1.0825	1.080	1.078
12	1.0937	1.091	1.091	1.0909	1.0906	1.091	1.090	1.091	1.0902	1.093	1.0901	1.0906	1.088	1.085
13	1.1023	1.100	1.100	1.0992	1.0989	1.099	.....	1.100	1.0984	1.100	1.0983	1.0988	1.096	1.094
14	1.1111	1.106	1.108	1.1111	1.1074	1.107	.....	1.108	1.1068	1.107	1.1067	1.1071	1.104	1.101
15	1.1200	1.116	1.116	1.1163	1.1159	1.116	1.114	1.116	1.1153	1.114	1.1152	1.1155	1.113	1.109
16	1.1290	1.125	1.125	1.1250	1.1246	1.125	.....	1.125	1.1240	1.122	1.1239	1.1240	1.121	1.118
17	1.1382	1.134	1.134	1.1339	1.1335	1.134	.....	1.134	1.1328	1.136	1.1326	1.1326	1.130	1.126
18	1.1475	1.143	1.143	1.1429	1.1424	1.143	1.141	1.142	1.1417	1.143	1.1415	1.1414	1.138	1.134
19	1.1570	1.152	1.152	1.1520	1.1516	1.152	.....	1.152	1.1507	1.150	1.1506	1.1504	1.147	1.143
20	1.1666	1.162	1.161	1.1613	1.1608	1.161	1.162	1.162	1.1600	1.158	1.1598	1.1596	1.157	1.152
21	1.1764	1.171	1.171	1.1707	1.1702	1.170	1.170	1.171	1.1693	1.172	1.1691	1.1690	1.166	1.160
22	1.1864	1.180	1.180	1.1803	1.1798	1.180	1.179	1.180	1.1788	1.179	1.1786	1.1785	1.176	1.169
23	1.1965	1.190	1.190	1.1901	1.1895	1.190	1.190	1.190	1.1885	1.186	1.1883	1.1882	1.185	1.178
24	1.2068	1.199	1.199	1.2000	1.1994	1.200	1.200	1.200	1.1983	1.201	1.1981	1.1981	1.195	1.188
25	1.2173	1.210	1.210	1.2101	1.2095	1.210	1.210	1.210	1.2083	1.208	1.2080	1.2082	1.205	1.197
26	1.2280	1.221	1.221	1.2203	1.2197	1.220	.....	1.220	1.2184	1.216	1.2182	1.2184	1.215	1.206
27	1.2389	1.231	1.231	1.2308	1.2301	1.230	.....	1.231	1.2288	1.231	1.2285	1.2288	1.225	1.216
28	1.2499	1.242	1.242	1.2414	1.2407	1.241	1.241	1.241	1.2393	1.238	1.2390	1.2390	1.235	1.225
29	1.2612	1.252	1.252	1.2522	1.2514	1.252	.....	1.252	1.2500	1.254	1.2497	1.2502	1.245	1.235
30	1.2[illegible]27	1.261	1.261	1.1632	1.2624	1.263	1.260	1.263	1.2608	1.262	1.2605	1.2612	1.256	1.245
31	1.2844	1.275	1.275	1.2743	1.2735	1.274	1.273	1.274	1.2719	1.269	1.2716	1.2724	1.267	1.256
32	1.29[illegible]2	1.286	1.286	1.2857	1.2849	7.285	1.284	1.285	1.2831	1.285	1.2828	1.2838	1.278	1.267
33	1.3083	1.298	1.298	1.2973	1.2964	1.296	1.296	1.297	1.2946	1.293	1.2943	1.2954	1.289	1.277
34	1.3207	1.309	1.309	1.3091	1.3081	1.308	1.307	1.308	1.3063	1.309	1.3059	1.3072	1.300	1.288
35	1.3333	1.321	1.321	1.3211	1.3201	1.320	1.315	1.320	1.3181	1.317	1.3177	1.3190	1.312	1.299
36	1.3461	1.334	1.334	1.3333	1.3323	1.332	1.329	1.3[illegible]2	1.3302	1.334	1.3298	1.3311	1.324	1.310
37	1.3592	1.346	1.346	1.3458	1.3447	1.345	1.339	1.345	1.3425	1.342	1.3421	1.3434	1.337	1.321
38	1.3725	1.359	1.359	1.3585	1.3574	1.358	1.359	1.357	1.3551	1.359	1.3546	1.3559	1.349	1.333
39	1.3861	1.372	1.372	1.3714	1.3703	1.371	1.372	1.370	1.3679	1.368	1.3674	1.3686	1.361	1.345
40	1.3999	1.384	1.384	1.3846	1.3834	1.384	1.375	1.383	1.3809	1.386	1.3804	1.3815	1.375	1.357
41	1.4141	1.398	1.398	1.3981	1.3968	1.397	1.399	1.397	1.3942	1.395	1.3937	1.3947	1.388	1.369
42	1.4285	1.412	1.412	1.4118	1.4104	1.410	1.413	1.410	1.4077	1.413	1.4072	1.4082	1.401	1.381
43	1.4433	1.426	1.426	1.4267	1.4244	1.424	1.427	1.424	1.4215	1.422	1.4210	1.4219	1.414	1.395
44	1.4583	1.440	1.440	1.4400	1.4386	1.438	1.441	1.438	1.4356	1.441	1.4350	1.4359	1.428	1.407
45	1.4735	1.454	1.454	1.4545	1.4530	1.453	1.455	1.453	1.4500	1.451	1.4493	1.4501	1.442	1.420
46	1.4893	1.470	1.470	1.4694	1.4678	1.468	1.466	1.468	1.4646	1.470	1.4640	1.4645	1.456	1.434
47	1.5053	1.485	1.485	1.4815	1.4829	1.483	1.482	1.483	1.4795	1.480	1.4789	1.4792	1.470	1.448
48	1.5217	1.501	1.501	1.5000	1.4983	1.498	1.500	1.498	1.4949	1.500	1.4941	1.4942	1.485	1.462
49	1.5384	1.516	1.516	1.5158	1.5140	1.514	1.515	1.514	1.5104	1.510	1.5097	1.5096	1.500	1.476
50	1.5555	1.532	1.532	1.5319	1.5301	1.530	1.532	1.530	1.5263	1.531	1.5255	1.5253	1.515	1.490
51	1.5730	1.549	1.549	1.5484	1.5465	1.546	1.550	1.540	1.5425	1.541	1.5417	1.5413	1.531	1.505
52	1.5909	1.566	1.566	1.5652	1.5632	1.563	1.566	1.563	1.5591	1.562	1.5583	1.5576	1.546	1.520
53	1.6092	1.583	1.583	1.5824	1.5802	1.580	1.586	1.580	1.5760	1.573	1.5752	1.5742	1.562	1.535
54	1.6279	1.601	1.601	1.6000	1.5978	1.598	1.603	1.597	1.5934	1.594	1.5925	1.5912	1.578	1.551
55	1.6471	1.618	1.618	1.6179	1.6157	1.616	1.618	1.615	1.6111	1.616	1.6101	1.6086	1.596	1.567
56	1.6667	1.638	1.637	1.6363	1.6340	1.634	1.639	1.634	1.6292	1.627	1.6282	2.6264	1.615	1.583
57	1.6868	1.659	1.656	1.6551	1.6527	1.653	1.660	1.652	1.6477	1.650	1.6467	1.6446	1.634	1.600

Note.—Where the modulus was not given, it was calculated by the formula $n = \frac{P \times d}{P - 1}$, in which n = modulus, P = specific gravity, d = Baumé degree (°). 66 was taken for d whenever the corresponding specific gravity appeared.

The next table gives a similar comparison for liquids lighter than water with, also, the pounds weight per gallon. In metric measure the specific gravity also measures the weight of the litre in kilogrammes.

SPECIFIC GRAVITIES AND DENSITIES, PER BAUMÉ.

Density.		Lbs. in one Gallon.	Density.		Lbs. in one Gallon.
B.	S. G.		B.	S. G.	
10	1.0000	8.33	44	.8045	6.70
11	.9929	8.27	45	.8000	6.65
12	.9859	8.21	46	.7954	6.63
13	.9790	8.16	47	.7909	6.59
14	.9722	8.10	48	.7865	6.55
15	.9655	8.00	49	.7821	6.52
16	.9589	7.99	50	.7777	6.48
17	.9523	7.93	51	.7734	6.45
18	.9459	7.88	52	.7692	6.41
19	.9395	7.83	53	.7650	6.37
20	.9333	7.78	54	.7608	6.34
21	.9271	7.72	55	.7567	6.31
22	.9210	7.67	56	.7526	6.27
23	.9150	7.62	57	.7486	6.24
24	.9090	7.57	58	.7446	6.21
25	.9032	7.53	59	.7407	6.18
26	.8974	7.48	60	.7368	6.15
27	.8917	7.43	61	.7329	6.12
28	.8860	7.38	62	.7290	6.09
29	.8805	7.34	63	.7253	6.05
30	.8750	7.29	64	.7216	6.02
31	.8695	7.24	65	.7179	5.99
32	.8641	7.20	66	.7142	5.95
33	.8588	7.15	67	.7106	5.92
34	.8536	7.11	68	.7070	5.89
35	.8484	7.07	69	.7035	5.86
36	.8433	7.03	70	.7000	5.83
37	.8383	6.98	75	.6829	5.70
38	.8333	6.94	80	.6666	5.55
39	.8284	6.90	85	.6511	5.42
40	.8235	6.86	90	.6363	5.30
41	.8187	6.82	95	.6222	5.18
42	.8139	6.78	100	.6087	5.01
43	.8092	6.74			

101. Densities of Commercial Oils are often determined by the more accurate method of determining specific gravity by weighing on the chemist's balance. A standard temperature is usually adopted, and all results reduced to standard by first determining the coefficient of expansion, which for pure olive-oil has been determined by Mr. C. M. Still-

well to be 0.00063 for 1° Centigrade, or 0.00035 per degree Fahrenheit.

Mr. Stillwell's determinations are given in the following table:

SPECIFIC GRAVITY OF ANIMAL AND VEGETABLE OILS.

Coeff. of Exp. = .00063 for 1° C. = .00035 for 1° F.	15° C. 59° F.
Sperm, bleached, winter	.8813
" natural, winter	.8815
Elaine	.9011
Red, saponified	.9016
Palm	.9046
Tallow	.9137
Neat's-foot	.9142
Rape-seed, white, winter	.9144
Olive, light greenish yellow	.9144
Olive, dark green	.9145
Pea-nut	.9154
Olive, virgin, very light yellow	.9163
Rape-seed, dark yellow	.9168
Olive, virgin, dark clear yellow	.9169
Lard, winter	.9175
Sea elephant	.9199
Tanners' (cod)	.9205
Cotton-seed, raw	.9224
Cotton-seed, refined, yellow	.9230
Salad (cotton-seed)	.9231
Labrador (cod)	.9237
Poppy	.9245
Seal, natural	.9246
Cocoa-nut	.9250
Whale, natural, winter	.9254
Whale, bleached, winter	.9258
Cod-liver, pure	.9270
Seal, racked	.9286
Cotton-seed, white, winter	.9288
Straits (cod)	.9290
Menhaden, dark	.9292
Linseed, raw	.9299
Bank (cod)	.9320
Menhaden, light	.9325
Porgy	.9332
Linseed, boiled	.9411
Castor, pure cold-pressed	.9667
Rosin, third run	.9887

The mineral oils are usually lighter than those of animal or vegetable origin.

The following are the densities of some of the compounds found in petroleums:

MINERAL OILS, 60° F., 15° C.

	S. G.	B.
Rhigoline	.6220	95
Benzine	.6510	85
Naphtha	.7000	70
"	.7500	57
Illuminating Oil	.8000	45
Lubricating Oil (heaviest)	.8860	26
Paraffine Wax	.8900	27

The "sperm"-oils of the market vary considerably in density, partly in consequence of natural differences due to differences in age, size, health, and condition of the sperm-whale which may have supplied all or part of the oil, and partly because of variations in the character and extent of the adulteration. Professor Ordway found "spindle-oils" to vary in density from 0.840 to 0.92, averaging 0.880. Ten so-called sperm-oils varied from 0.880 to 0.896, averaging 0.884. Oils from newly arrived cargoes ranged from 0.877 to 0.888. Lard-oils average 0.917, ranging from 0.914 to 0.920. Neat's-foot oil gives an average of 0 912, ranging from 0.910 to 0.920 for a sample known to be pure. The addition of refined, odorless, heavy mineral oils to other lubricants is a usual cause of increase of density; this is particularly the case with lard-oil. The common method of making these determinations is by the use of the "1000-grain bottle," or other such apparatus.

In using the various areometers as oleometers, large jars and densimeters having slender, finely graduated stems should be employed, their scales reading to 0.001. This can be done by constructing the instrument as an oleometer purely, thus being able to distribute a small range of density over an extended scale. Special oleometers are sometimes made for the mineral oils, and others for the organic oils.

102. The Viscosity of Oil is generally closely related to its density, but is not proportional to specific gravity, and is

occasionally found to decrease with increase of density. The relative viscosity of oils may be determined with some degree of accuracy by simply filling a pipette with the oils to be compared, one after another, and permitting them to flow out through a small opening, noting the time required to discharge equal quantities. A very complete apparatus for this purpose is that exhibited in Fig. 30, a form adopted by Mr. J. V. Wilson.

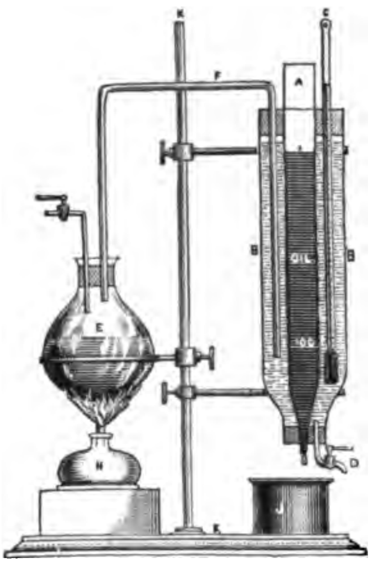

FIG. 30.—VISCOSITY OF OILS.

In the figure, *A* is a glass tube about 1 in. diameter, graduated from 1 to 100, to contain about 100 cubic centimetres of oil. *BB* is a glass jacket, about 3 in. diameter, filled with water as shown; *C* a thermometer, indicating temperature of water in jacket; *D* a small brass cock for withdrawing water from jacket; *E* a glass flask for generating steam to heat water in jacket; *F* a glass pipe connecting the steam flask *E* with jacket *B*, delivering at bottom of jacket; *G* is a small cock for permitting escape of steam in order to regulate quantity sent into jacket; *H* a spirit-lamp on a stand; *J* a glass beaker to contain oil, and *KK* cast-iron stand, with adjustable arms, for carrying the apparatus.

The following table gives the time required, by each of several oils, to flow through the orifice of the above-described apparatus, and the temperature observed in the same oils when used on a journal 3 in. (7.2 cm.) diameter, making 1500 revolutions per minute, the average being noted for an hour and a half. It is seen that, as a rule, the more viscous the oil the more heat developed by friction. The stearine found in tallow-oil may cause the apparent discrepancy noted there.

VISCOSITY OF OILS.

Name of Material.	S. G. at 60° F., 15° C.	Rate of Flow.			Temperature Developed by Test.	
		60° F., 15° C.	120° F., 49° C.	180° F., 82° C.	Fahr.	Cen.
Water	1000	....	......	......	......	.....
Castor Oil	960	....	132	41	158	70
Rosin Oil	990	....	.. ..	......	155	68
Engine Tallow	....	Solid	41	26	......	.....
Tallow or Animal Oil	....	143	37	25	141	61
Neat's-foot Oil	....	112	40	29	......	.....
Rape Oil	916	108	41	30	148	64
Lard Oil	916	96	38	28	146	63
Olive Oil	915	92	37	28	143	62
Sperm Oil	880	47	30	25	133	56
Mineral Oil	905	45	......	......	121	49
"	875	30	......	......	117	47

It is sometimes customary to make the viscosity of oils a standard test of quality. In such cases it is usual to compare the oils so tested with some well-known oil, as rapeseed, as a standard of value. In these cases the size of the containing vessel, of the nozzle and its orifice, the head producing flow, the material of which they are made, the temperature, and other conditions should be carefully specified and made as nearly constant as possible. The specific gravity of the oil should be ascertained and stated.

It has been proposed to adopt a standard "viscosimeter" * of dimensions as follows:

A glass cylinder, 22 in. (55.9 cm.) long, $1\frac{1}{4}$ in. (3.18 cm.) diameter, has a brass lower head $\frac{1}{8}$ in. (0.318 cm.) thick. An orifice is bored in the centre $\frac{1}{16}$ in. (0.794 cm.) in diameter, with bevelled edges chamfered back $\frac{1}{2}$ in. (1.27 cm.), thus producing a sharp-edged orifice. A line marking the 18-in. (45.72 cm.) level is cut with several finer lines above and below, $\frac{1}{8}$ in. (0.318 cm.) apart, ranging from 16 to 21 in. (40.64 to 53.34 cm.) above the orifice. The standard temperature is usually 60° F. (15.5° C.). A total flow of as nearly 100 c.c. (6.103 cu. in.) is secured by adjusting the supply so that the head shall be as nearly as possible equal to 18 in. (45.72 cm.) of water, deter-

* *Chemical News*, 1884. W. P. Mason.

mining this head by calculation from the specific gravity of the oil.

Note the time required to discharge the 100 c.c. (6.103 cu. in.), and divide this time by that required where water under a head of 18 in. (45.72 cm.) is used. This ratio is the measure of the viscosity.

Large consumers of oil sometimes purchase on the basis of this kind of test solely. It is regarded as quite as satisfactory and reliable as any single physical or chemical test known, and as second only to the best testing-machine methods.

The less the viscosity, consistently with the use of the oil under the maximum pressures to be anticipated, the less is, usually, the friction. The best lubricant, as a rule, is that having least viscosity combined with greatest adhesiveness. Vegetable oils are more viscous than animal, and animal more so than mineral oils. The fluidity of an oil is thus to a large extent a measure of its value.

The close relation between the viscosity and the friction-reducing power of the oils is well shown in Fig. 31, which graphically exhibits this relation as determined by Mr. C. N. Waite.* The curves show the relation between the viscosity and lubricating power of lard and of light paraffine oil; the full lines represent the readings on the machine, at different temperatures, multiplied by a constant, and the dotted lines the viscosity of the oil. The curves are approximately correct. The true curves are probably smooth, and their form mathematically determinable.

The relation of viscosities of oils at ordinary temperatures is not a measure of their relative standing in this respect at higher temperatures, as in steam-cylinders. Oils of great viscosity at low temperatures are often very limpid when heated. Tallow and castor oils are more viscous than sperm when cool, but they become very much more fluid when heated, as in steam-cylinders.

103. Gumming, or Drying, is a method of alteration of oils usually caused, as already stated, by the absorption of oxy-

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* Proceedings N. E. Cotton Manufacturers' Association, No. 28, 1880.

gen and the gradual conversion of the oil into resin. It goes on rapidly with the "drying"-oils, slowly with the fixed animal and vegetable oils, and is not observed in any important

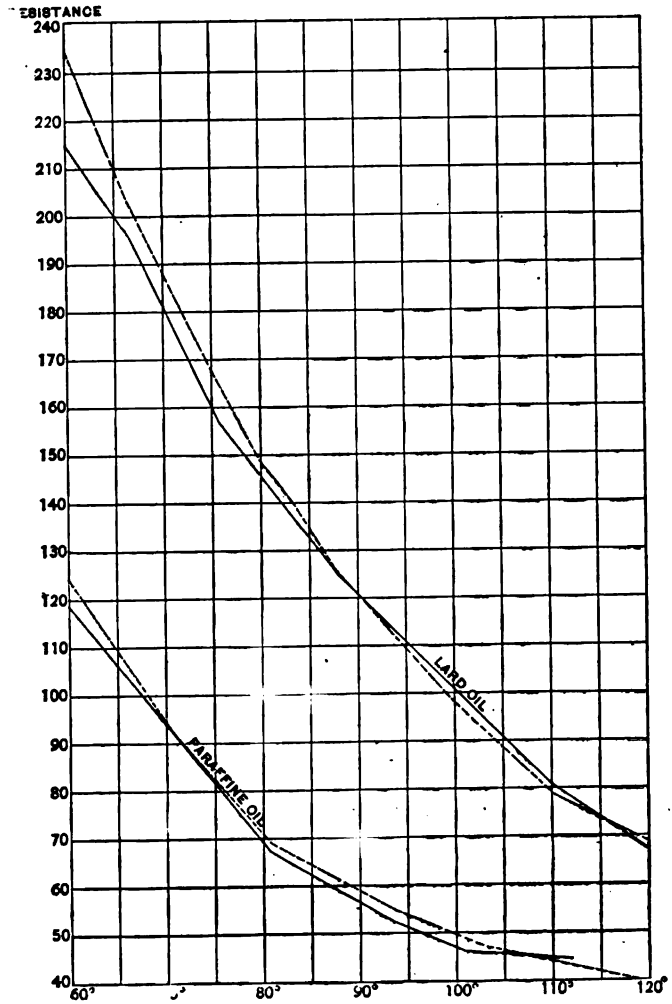

FIG. 31.—VISCOSITY AND LUBRICATION.

degree in the mineral oils. This gradual increase of viscosity and tendency to final conversion into the solid form is one of the phenomena noted by the inspector in his examination of

lubricants. The methods of determination of the character of the lubricant in this respect, as practised by various observers, differ greatly. The most satisfactory method is probably that in which the lubricant-testing machine is employed: this method, as conducted by the Author, is simply to test the oil as received: then to expose the journal, still wet with oil, to the action of the air, but keeping it protected from dust, one day or more, according to the kind of oil, and then to again test its friction-reducing power. This process will be fully described later (Arts. 132, 136).

104. Nasmyth's Apparatus for observing the viscosity and gumming of oils is very simple. The observer places a drop at the top of an inclined plane, and notes the time required for it to run down the plane. Of oils which do not gum, the least viscous reach the bottom first. Drying and gumming oils are retarded in proportion to the rate of drying or of gumming. Nasmyth used a plate of iron 4 inches wide by 6 feet long, on the upper surface of which six equal-sized grooves are planed. This plate is placed in an inclined position—say, 1 inch in 6 feet.

The mode of testing is as follows: Assume that six varieties of oil are to be tested, to determine which of them will for the longest time retain its fluidity when in contact with iron and exposed to the action of air; pour out *simultaneously*, at the upper end of each inclined groove, an equal quantity of each of the oils under examination. This is very conveniently done by the use of a row of small brass tubes. The six oils then make a fair and even start on the race down-hill: some are ahead the first day, and others are still ahead the second and third day; but on the fourth or fifth day the bad oils begin to fall behind by gradual coagulation, while the good oil holds on its course: at the end of eight or ten days there is no doubt left as to which is the best. Linseed-oil, which makes capital progress the first day, is, in the case given, set fast after having travelled 18 inches, while second-quality sperm overreaches first-quality sperm by 14 inches in nine days, having traversed in that time 5 feet 8 inches. The following table shows the state of the oils after a nine days' run:

VISCOSITY OF OILS.*

Description of Oil.	First Day.		Second Day.		Third Day.		Fourth Day.		Fifth Day.		Sixth Day.		Sev'th Day.		Eighth Day.		Ninth Day.	
	ft.	in.	ft.	in.	ft.	in.	ft.	in.	ft.	in.	ft.	in.	ft.	in.	ft.	in.	ft.	in.
Best Sperm Oil.......	2	8⅛	4	2	4	5¾	4	6	4	6	4	6	4	6⅛	stat.		....	
Common Sperm Oil...	1	7	3	9	4	6¾	4	11	5	1⅛	5	4	5	6¾	5	7⅝	5	8
Gallipoli Oil.....	0	10¼	1	2¼	1	6	1	6⅛	1	7⅝	1	8¾	1	9	1	9¼	1	9⅛
Lard Oil............	0	10¼	0	0⅛	0	10¾	0	10¾	0	11¾	stat.		....		....		....	
Rape Oil.............	1	2½	1	6¼	1	7	1	7⅛	1	7¼	1	7¼	1	7¼	1	7¾	stat.	
Linseed Oil.	1	5⅛	1	6	1	6¾	1	6¾	1	6⅛	1	6¼	1	6¼	stat.		....	

This process is used by the Author. He adopts a surface of glass, however, instead of metal.

A modified apparatus is described by Mr. W. H. Bailey, and is illustrated in Fig. 32. It consists of a piece of plate-glass set with considerable inclination, and heated, by means of a vessel of boiling water, to about 200° F. (93° C.), and held at a uniform temperature, as indicated by the thermometer attached. A drop of oil placed at the top will flow down a few

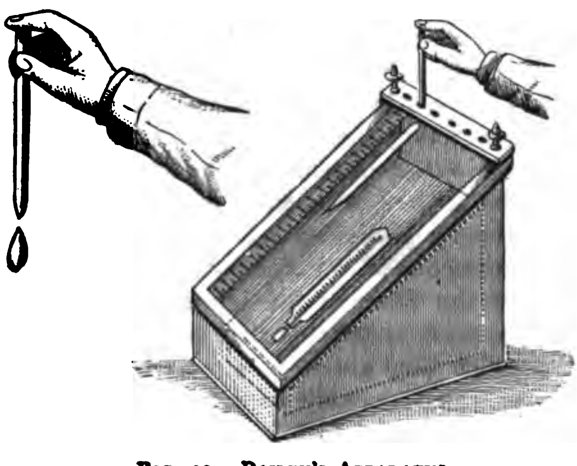

Fig. 32.—Bailey's Apparatus.

inches, as in Napier's test, and if permitted to remain upon the glass some days will give evidence of any existing tendency to gum. A scale on the side of the box affords a convenient means of measuring the track of the flowing drop. Watch-oil is tested in Switzerland somewhat similarly. If the oil is found

* Appleton's Dictionary of Mechanics, vol. II.

to become decidedly resinous after two or three days' exposure to heat, it is condemned.

A very simple and commonly used test of the fluidity of the oil consists in dipping into it a piece of blotting-paper, and watching the falling drops as it is held above the surface of the oil. Should the oil fall in distinct, symmetrical, pearl-like drops, it is an evidence of fluidity; a tendency to spread is the indication of viscidity. Retaining the oil on the paper at a temperature of 200° F. for some hours, or at ordinary temperature for some days, will enable the observer to judge of the rate of gumming.

Oil may also be tested by being kept warmed, nearly to the boiling-point, in a watch-glass: if it gums in the course of two or three days it should be condemned.

105. **The Effect of Heat,** and of variation of temperature, is very observable with all the fats and oils. Their classification into oils, fats, greases, butters, and fatty waxes is based upon the assumption that they are observed at ordinary temperatures. An increase of temperature converts the greases and the waxes into oils, and the reverse change solidifies the oils, converting them into greases, or even into hard, waxy solids. Variation of temperature affects every lubricant in an important degree, also, in other respects. It changes the friction-reducing power, as well as the fluidity of the unguent, and is thus one of the elements necessarily considered in determining the value of the lubricant. For out-of-door work, unguents must be selected that will "feed" at any temperature to which they are to be exposed in the working of the bearing to which they are supplied; it is not advisable, therefore, to use the same lubricant in winter as in summer. Steam-cylinders are best lubricated with mineral oils of heavy body and high "fire-test," which test is resorted to with all mineral and often with other oils.

The effect of heat upon the viscosity of oils gives a good illustration of the sensitiveness of the oils to changes of temperature; and when it is known that the viscosity and the lubricating power of any oil are usually very closely related, it is seen that change of temperature has an exceedingly important

effect upon lubricating oils and greases. Fig. 33 exhibits the relation of viscosity to temperature in the cases of a number of well-known oils. The "spindle-oils" are mineral oils.

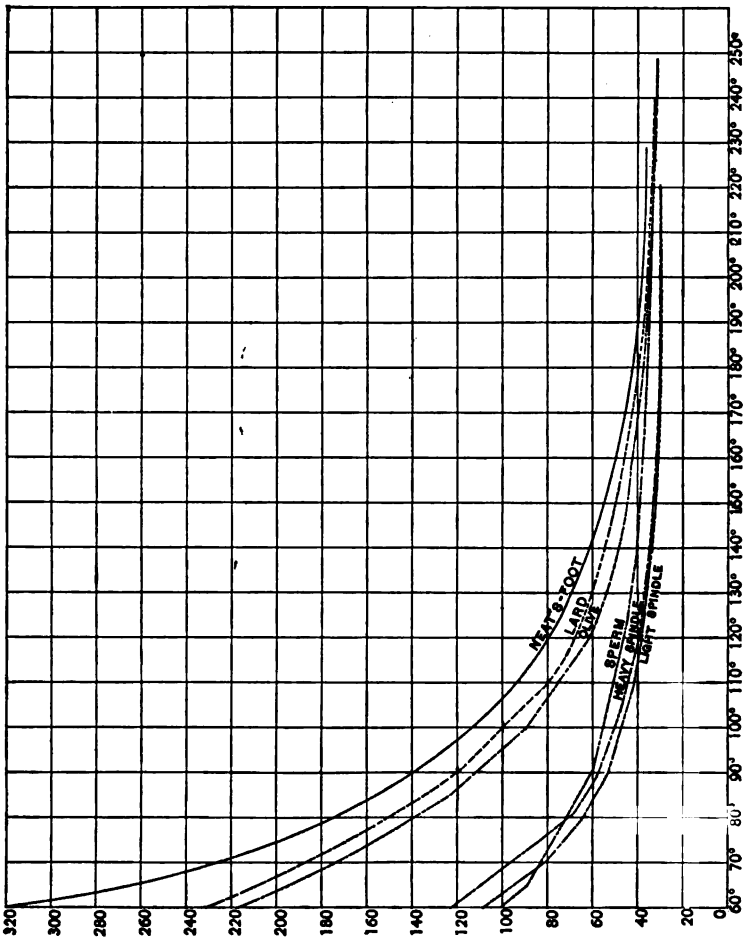

Fig. 33.—Effect of Temperature on Viscosity.

At 60° F. (15° C.) the viscosity of sperm being 1.00, neat's-foot is 3.20; lard, 2.30; olive, 2.18; paraffine 25° grav., 1.23; paraffine 29° grav., 1.06. As the temperature rises the viscosity decreases, neat's-foot being most and sperm least affected

by variations in temperature. While at 60° F. sperm is 20 per cent. thinner than the heavy paraffine, yet at 100° F. (38° C.) it is 10 per cent. thicker, the viscosity of the paraffine having diminished so much more rapidly than that of sperm. At 250° F. (121° C.) the oils are all of nearly equal viscosity. The effect of heat on the lubricating value of the oils will be exhibited later.

It is in consequence of this sensitiveness to heat that the testing-machine used by the Author, and described later, has

FIG 34.

often been fitted with Hirn's "water-brasses" for the purpose of keeping temperature constant when comparing lubricants.

106. The "Fire-test" determines the temperature at which the mineral oils discharge vapors by fractional distillation, and that at which the other oils decompose and take fire.

This "fire-test" is usually made with a piece of apparatus made especially for the purpose. That of Guiseppe Tagliabue is shown in Fig. 34. It consists of a little tank in which the oil to be tested is poured. This is placed in another large cup, and the space between is filled with water, for ordinary tests. A lamp beneath supplies the heat, and a thermometer set in the cup with its bulb in the oil shows the temperature.

As the oil becomes heated the observer occasionally applies

a lighted match or taper to the opening of the cup. After a time a flash is seen when the match is applied, and the flame disappears as suddenly as it has appeared. This shows that vapor has been produced in sufficient quantity to mix with the air above the oil and produce an explosive mixture. The temperature now observed is called the "flashing-point." At some higher temperature, if the cap is moved to one side and a match is applied, the oil takes fire and burns. This is the so-called "burning-point." It may be many degrees above the flashing-point.

Many different forms of instrument are in use, some of which are described by State regulations, which also prescribe the method of test. The closed cup, above described, gives a lower apparent flashing or burning point than is obtained with an open cup. The electric spark has been used by several physicists for igniting the vapor. The rate of heating should be about 20° F. (11° C.) in a quarter of an hour.

This method of test is most generally adopted in the examination of the mineral oils, which oils are liable to ignition if not properly distilled, and thus to give rise to dangerous accidents. Lubricating oils defective in this respect have sometimes set fire to factories when used on heating journals. When such oils are used, their evaporation often produces a dangerously large quantity of combustible vapor in the adjacent atmosphere, and this, if fired, may cause a serious conflagration. Such oils, in burning, exaggerate the dangers and the difficulties of the situation by their vaporization. A high fire-test and minimum evaporation indicates a good, as well as a safe, lubricant.

The loss by evaporation of a mineral oil may be ascertained by placing a known weight in a watch-glass, and maintaining it at a constant temperature for a definite period, as at 140° F. (60° C.) for twelve hours. Under such conditions the loss may be below one per cent., or it may exceed 25 per cent. A good mineral oil should never lose 5 per cent.

Other oils always gain weight by absorption of oxygen and by resinification. They are sometimes subjected to the fire-test to ascertain whether they have mineral oils mixed with

them. The following are figures obtained by the Author with the apparatus just described:

FIRE-TESTS OF OIL.

Oils.	Temperatures—Fahr. and Cent.					
	Flash.		Take Fire.		Burn.	
	F.	C.	F.	C.	F.	C.
West Va. Oil	245°	118°	290°	143°	300°	149°
Winter Sperm	400–425°	219°	485°	252°	500–520°	260°
Lard	475°	246°	525°	274°	525°	274°

The flashing and the burning points and the temperature of decomposition can thus be found, and liability to injury by heat determined, or safety in the presence of fire. The standard animal and vegetable oils and all mineral oils of good "body" and density only decompose or vaporize at a temperature exceeding that of the steam in ordinary steam-engines, and even steam at locomotive pressure. The heavy refined mineral oils are best for the latter application.

Illuminating oils, consisting partly or wholly of petroleums, are seldom permitted to be sold when having a fire-test below 150° F. (66° C.); and lubricating oils are often rejected by purchasers if falling under 300° F. (149° C.), or losing by evaporation more than 5 per cent. when kept at a temperature of 140° F. (60° C.) 12 hours. This latter may be also considered a standard method of test.

A winter test of 250° F. (121° C.) and a summer test of 300° F. (149° C.) are usual figures.

107. "**Cold-tests**" are made, in some cases, to determine the behavior of oil and greases at low temperatures, and whether they may be used out of doors in cold weather. All the animal and vegetable oils solidify with reduction of temperature, and usually at but moderately low temperature. The greases are hardened by cold. The good mineral oils do not congeal at any ordinarily low temperatures, the heavier oils freezing at 20° F. (— 6°.6 C.) and the lighter remaining liquid at 0° F. (— 18° C.). Summer sperm thickens at about 65° F. (18° C.), freezing at about 50° F. (10° C.); winter sperm

at about 50° and 35° F. (1°.6 and 10° C.); and lard-oil begins to harden at 40° F. (4°.4 C.) solidifying at 25° F. (– 4° C.).

A good test of capacity to resist low temperatures is as follows: Fifteen parts of Glauber's salts are put into a small glass vessel, a small bottle of the oil to be tested is immersed in this; a mixture of five parts of muriatic acid and five parts of cold water is placed over the salt. The temperature is reduced slowly, and when very low the behavior of the oil may be observed and noted. Ice alone, or a mixture of ice and common salt will prove, probably, equally good.

Tests of several oils, made at the U. S. Navy Yard, Brooklyn, in 1870, gave the following:

Oils.	Thickens. C.	Thickens. F.	Flow Ceases. C.	Flow Ceases. F.	Solid. C.	Solid. F.	Sp. Gr.
Sperm, Natural..	1°	34°	– 3°	26°	– 9°	16°	0.761
Olive............	10°	50°	– 8°	18°	– 14°	6°	0.933
Tallow..........	– 1°	30°	– 4°	24°	– 8°	18°	0.795
"	21°	70°	16°	60°	6°	42°	0.993
Lard............	7°	44°	0°	32°	– 6°	22°	0.959

Good mineral oils do not solidify at the freezing-point of water.

The best method of test is to first freeze and then, warming the oil, note its melting-point.

108. Tests with Acid.—The addition of concentrated sulphuric acid to oils was found by Maumené and by Fehling to produce considerable heat, and they were able to distinguish them by measuring the resulting increase of temperature. The drying-oils heat most, and disengage sulphurous acid. The following determinations are given by Chateau:

ACID TESTS OF OILS.

Oils.	Increase of Temperature. Maumené.	Increase of Temperature. Fehling.
Olive....................................	42° C.	37°.7 C.
Poppy....................................	74°.5	37°.7
Colza....................................	58°	37°.7
Almond....................................	53°.5	40°.3
Rape-seed....................................	57°	55°
Linseed....................................	133°	74°
Sesame....................................	68°	74°
Castor....................................	47°	74°
Cod-liver....................................	103°	74°

Maumené added 10 c.c. of acid to 50 grs. of each oil. Fehling used but 15 grs. of oil. The acid had a density of 66° B. The results are thus not precisely comparable; but it seems evident that this method is either not at all accurate, or was not well practised by one or the other of these investigators.

Coleman describes* similar tests, in which he added sulphuric acid to rape and to olive oil, and observed a rise of 100° and 68° F. (37°.7 and 20° C.) respectively. The same experimenter saturated cotton-waste with oil and raised its temperature to 150° or 200° F. (65°.5 or 93° C.) in an air-bath, noting the time required to produce spontaneous ignition and combustion. Boiled linseed-oil took fire in 1¼ hours, raw oil in 4 hours, while refined rape-seed oil required 9 hours of exposure. The addition of 20 per cent. mineral oil greatly retarded and 50 per cent. entirely prevented ignition.

109. **Oleography** constitutes another, and a very beautiful, although rarely practised, method of identifying oils of various kinds; it was introduced many years ago by Professor Tomlinson, who first applied it to the exhibition of the characteristic differences between the essential oils, and termed the peculiar and beautiful forms thus produced "cohesion-figures."

It was again brought forward by Dr. Moffat,† and by him applied to the identification of the commercial oils and the detection of adulteration. The process, as perfected by Dr. Moffat, is now familiar under the name of "oleograph-test." We proceed thus: Wash out a large basin very carefully with water and alkali until it is chemically free from foreign matter, and fill with perfectly clean water. When the surface has become quiet, drop upon it a single drop of the oil to be examined. The oil at once spreads rapidly over the surface of the water in an exceedingly thin film. Presently the film commences breaking up, small openings appearing through it, which gradually enlarge and group themselves into peculiar lace-like patterns. These lace-patterns continue changing, and finally the surface of the water is covered with detached and very minute

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* Trans. Phil. Soc. of Glasgow, 1873.

† *Chemical News*, vol. xviii. p. 299.

particles of oil. Each oil, under the same set of standard conditions, exhibits a peculiar behavior that is always characteristic of the oil, and which can therefore be made of use in identifying it. Each oil spreads at a certain rate, and each, at a certain instant during the process of change, forms a peculiar and characteristic lace. A comparison of the pattern produced in testing the several oils and of the times of observation enables the experimenter to judge, by comparison with his standards, whether the oils tested in this way are pure or adulterated.

In doing this work it is important to be able to secure copies of the patterns thus obtained. This is done by a very simple and neat process: Provide another basin containing water rather strongly colored with ink, and a quantity of white blotting-paper cut into pieces of such size and shape that they can be laid upon the surface of the water in the testing-basin.

The observer stands, watch in hand, noting the changes progressing in the film of oil. At the proper moment—a half-minute, a minute, or two minutes, whichever may have been found a proper standard time, measured from the falling of the drop—he carefully and quickly lays a piece of his blotting-paper down on the film, then as quickly and carefully transfers it to the surface of the ink-solution. At the first contact every point in the surface transfers to the pages a particle of water or a particle of oil, and the lace-pattern is now present on the paper in oil and water. On placing the blotting-paper on the colored water all parts of the surface unprotected by oil are stained, while the rest remains uncolored; and the beautiful lace-pattern appears in black and white in permanent and preservable form. The sheet is next marked with the name of the oil, the date of the test, and the time allowed for the formation of the pattern. It still remains to be determined by further experiment how far the method may be made practically valuable and reliable.

The special precautions to be observed in practising this method of test are to secure an absolutely perfect cleanliness of the vessels used, and to note with care that oleographic figure which is most thoroughly characteristic of the oil under test; this is found to occur at one instant during the uninter-

rupted process of change of each film of oil, and the patterns which precede and which succeed it are comparatively valueless.

The vessels should be cleaned perfectly with a solution of caustic potash or soda after each experiment. The oil should be let fall in a single drop upon the exact centre of the surface of water from a glass rod, and in such a manner that no disturbance is produced. These rods, when not in use, should be kept in a solution of caustic potash, and when used should be drawn through clear water and wiped upon a clean cloth before dipping them in the oil.

Occasionally, when the vessels have been some time in use, it will be necessary to wash them and the rods in strong sulphuric acid;* they should then be thoroughly rinsed.

The symmetry of the figures produced, as well as their characteristic form, is injured or destroyed by adulteration, and sometimes by physical changes occurring under exposure to air, and with age. Solid carbolic acid and camphor treated in this manner yield curiously active spots and figures.

The time at which the distinctive figure is formed is an absolutely essential element, as already stated; and it is therefore always advisable first to prepare a set of standards by obtaining the oleographs of oils of known purity. The figures may be obtained in any desired color by using colored inks. They may be photographed, if desired, or may be transferred to the lithographer's stone.

110. The Forms of Cohesion-figures are very characteristic. In the experiments of Miss Crane, a single drop of oil was allowed to fall from a burette held at a distance of a few inches from the surface of a dish of clean water. The time required for the production of certain figures was carefully noted, as several oils will produce very similar figures ultimately, if sufficient time be given. Oil of turpentine spreads out instantly, and soon forms a beautiful lace-work. Oil of cinnamon forms a figure not more than half the size of the preceding oil. In a few seconds small portions are detached,

* *Chemical News*, vol. xiv. p. 64.

and separate into distinct drops. Cod-liver oil spreads into a large film; a little way from the edge small holes appear, and in a minute or two the surface is studded with them. These gradually enlarge, assume irregular shapes, and become separated by branching lines. As the oils give different figures, and behave differently when mixed with one another, or with lard-oil, this method may be of great value in preliminary testing of suspected oils.

111. Electricity is used in making tests of oil, by noting their differences of conductivity. Rousseau has shown that the oils, with the exception of olive-oil, which has about $\frac{1}{700}$th the conductivity of other oils, are good conductors of electricity, and has devised apparatus to detect adulterations of that oil, called the "diagometer." The instruments used are a galvanometer and a small voltaic battery, the current from which is passed through a drop of the oil to be tested, and its intensity measured by the galvanometer. A comparison with oils of known purity or of known composition gives the evidence sought.

Professor Palmieri has devised a new diagometer, which is used for rapid examination of oils and textures. It will show the quality of olive-oil; will distinguish olive-oil from seed-oil; will indicate whether olive-oil, although of the best appearance, has been mixed with seed-oil; will show the quality of seed-oils; and will also indicate the presence of cotton in silken or woolen textures.

Mr. F. S. Pease has devised a fire-test igniter, consisting of an oil and a water bath, thermometers, an induction-coil and battery, and wires for the purpose of testing mineral oils. The mineral oils are good conductors of electricity.

112. Machines for Testing Lubricants are now invariably used in making determinations of the coefficient of friction, and of its variation with varying pressures, temperatures, velocities of rubbing, and other conditions affecting the efficiency of the unguent, as well as in determining its endurance and its tendency to gum. These machines consist of a journal constructed as nearly as possible like those on which the unguent is to be used, arranged for lubrication in the customary

manner, or in the way in which the journals to be lubricated are "fed," and with apparatus to exhibit the variations of speed, temperature, and friction. The aim is always to make the test under the actual conditions of practice, as nearly as possible. There are a number of forms of these machines, some of which will be described in a later chapter, in which also the results of experiments conducted upon them will be given.

It is obvious that experiments made upon the nicely fitted journal of a testing-machine are not conclusive as to the fitness of a lubricant for use on a similar journal which is not well fitted. The latter bearing only in spots, or along lines of contact, is subjected on such surfaces of contact to pressures which may be enormously heavier than that affecting the same journal when wear or refitting has given it a good bearing, and the best lubricant is therefore one adapted to such intense pressure. Could its magnitude be known, a good testing-machine would determine which of any collection of oils is best fitted for use upon it. The testing-machine determines the behavior of an oil upon its own journals; if those on which the lubricant is to be used are similar, its behavior will then be the same. While the machine does not usually serve to select oils for badly made lubricated surfaces, it exhibits the intrinsic qualities of the oils tested; and every mechanic and engineer endeavors to get all journals into as good condition as those of the testing-machine, and thus fit them to do good work with good oils.

The measure of the coefficient of friction alone is not always a gauge of the value of an oil. A low coefficient is sometimes found to coexist with serious wear; and even low friction and a cool journal may be accompanied by wear. Whatever the condition of the journal, however, being reproduced in the testing-machine, the position of the lubricant in the scale of values may be ascertained. Any difference, whether of pressure, speed, temperature, or of form or material of rubbing surfaces, will demand for best effect some corresponding difference in the unguent.

With very light pressures and high speeds, as with fast-run-

ning spindles, light mineral oils sometimes give low friction, and yet produce rapid wear. Animal oils in such cases are used in solution in the mineral oils to give body and to reduce wear. Heavier machinery, as that of electric-light apparatus, at high speeds, may be best served with light oils very freely supplied, as by the oil-bath, which, indeed, should be adopted wherever possible.

CHAPTER VI.

EXPERIMENTS ON FRICTION—TESTING-MACHINES.

113. **The Earliest Experiments** on the now familiar methods of waste of work and energy by friction were made at the end of the eighteenth and the beginning of the nineteenth centuries. They were made without regard to the influence of what are now known to be essential conditions, and were therefore not adequate to determine the facts and laws of friction with the exactness and completeness that is desirable in the engineer's applications in the science and the art of construction.

The best-known experiments of earlier times are those of Coulomb on rolling friction, of Rennie on sliding friction of unlubricated surfaces, and those of Morin upon the friction of solids, both with and without lubrication.

114. **Rolling Friction; Carriages.**—Coulomb was the first to determine the law of rolling friction, and he found that, so long as the wheel or roller and the surface on which it rolled were not injured, the resistance was proportional to the weight, and diminished as the diameter of the wheel increased.

Coulomb and others have, as has been seen, found

$$R = f\frac{W}{r},$$

in which R is the resistance applied at the *circumference* of the wheel, W the total weight, r the radius of the wheel, and f a coefficient which is very variable, but may be taken as 0.06 for wood and 0.005 for metal, where the units are lbs. and feet, and $f = 0.02$, nearly, and $f = 0.002$ when in metric measures. Tredgold makes the value of f for iron on iron 0.002.

When the pressure becomes so great as to crush the fibres of the wood, the friction is increased irregularly, and cannot be estimated with any degree of accuracy.

Experiments similar to those made by Coulomb in 1781 were also made by Morin at the Conservatoire des Arts et Métiers, Paris, in which oak-rollers 9 inches (0.26 m.) in diameter were used under small loads, and rolling upon poplar rails. Morin also found that the resistance increased with diminishing bearing-surface.

With a bearing of 0.656 feet, or 9 inches, and loads of 350 to 450 lbs., the value of f was found to average 0.002874; with bearing of a total width of 0.081 feet, or 10 inches, and loads of 375 to 450 lbs., the value was $f = 0.006374$, both in British measures, or $f = 0.0009$, nearly, and $f = 0.002$, for metric units. The measure of this friction is the moment, Rr, which may be called the moment of rolling friction.

The same laws were, about 1840, found by Morin to be applicable to vehicles with little modification. He states that—

(1) On pavements and macadamized roads the resistance is proportional to the total weight of load and vehicle, is inversely proportional to the diameter of wheel, and is independent of the breadth of the tire. It increases with the velocity.

(2) On soft ground the resistance decreases with increase of breadth of tire, and is unaffected by the speed of the vehicle.

(3) The line of draught should be horizontal.

The conclusions relative to rolling resistance on hard roads are also applicable to railroads.

It follows that wheels should be made as large as possible, and the breadth of bearing as great as is needed to prevent crushing of the material. Morin found four-wheeled carts to be preferable to those having a single pair of wheels.* The value of f for wagons was, on soft soil, about 0.065 (0.02 for metric measures), but under very favorable conditions became as low as $f = 0.02$ (0.006 metric), which value may be taken for the friction of motion on smoothly paved and macadamized roads.

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* *Vide* Expériences sur la Tirage des Voitures, etc., A. Morin, 1842.

Later experiments upon more modern forms of vehicles give results as follows:

Debauve (1873) found the resistances on macadamized roads to vary from 0.033, or 70 lbs. per ton, for heavy carts, to 0.036, or 80, for carriages; and from 0.018 to 0.036, or 40 to 80, on paved streets, for the same classes of vehicles.

Tresca found the resistance of an omnibus to be, at ten miles an hour, 0.036, 80 to 85 lbs. per ton, on macadamized roads, and 0.03, 65 or 70, on paved streets.

The draught of heavy wagons becomes as high as 0.10—224 lbs. per ton, and usually is not far below 0.07—about 150 lbs. per ton on soft ground, as in fields.

A committee of the Society of Arts reported a loaded omnibus to exhibit a resistance * on various roads as below:

Pavement.	Speed.	Resistance.
On Granite paving	2.87 miles.	0.007 = 17.41 lbs. per ton.
" Asphalt	3.56 "	0.0121 = 27.14 " "
" Wood	3.34 "	0.0185 = 41.60 " "
" Macadamized, gravelled	3.45 "	0.0199 = 44.48 " "
" " granite, new	3.51 "	0.0451 = 101.09 " "

M. Lavallard (1884) found the resistance of omnibuses on various pavements and at various speeds to range from 1.5 to 1.9 per cent. of the total load, or from about 35 to about 45 lbs. per ton, averaging not far from 1.7 per cent., or $37\frac{1}{2}$ lbs. per ton. The horses used travelled about 16,000 metres (10 miles nearly) per day, doing work at the rate of from $\frac{1}{8}$ to $\frac{1}{14}$ horse-power, as developed by a steam-engine working 24 hours continuously.

Clark deduces from published experiments the formula

$$R = 30 + 4v + \sqrt{10v}.$$

in which the resistance, R, is given in pounds per ton, the velocity, v, being taken in miles per hour, and the road being assumed to be well macadamized. The same authority states that a good Flemish draught-horse will work at the rate of about 22 ton-miles per day in summer, and 28 in winter, aver-

* Clark's Manual for Mechanical Engineers, 1877.

aging 25 for the year, this work being the product of load transported by distance traversed.

115. A Railway Train in good order and on a good road will not be safe against starting under the action of gravity alone unless the gradient is less than 0.0035—18 or 20 feet to the mile; once started, it will continue in motion on gradients as low as 0.0024—13 feet per mile.

Wellington finds the resistance to starting twice or thrice the above with ordinary trains on fairly good track, and concludes that rolling friction forms but a small proportion of the total. Trautwine makes the rolling friction about one pound per ton, the remainder being journal and flange friction.

Rolling friction is usually overcome by an effort applied at the axis of the wheel or roller, as in cars, wagons, etc., but sometimes by a force applied at the circumference. In the latter case the "moment" or leverage of the applied force is greater, and its required intensity correspondingly reduced to one half the former.

Where journals are carried on friction-rollers, the rolling friction thus introduced is added to the total resistance; but the sliding-journal friction is reduced nearly in the proportion of the diameters of the friction-rollers to the diameters of the journals of the latter. The total work of friction, which is the product of the resistance into the distance through which that resistance is overcome, is thus often greatly reduced. In cases in which the frictional resistance is increased there will still be an economy of power if the work of friction can be at the same time lessened in a greater proportion.

The resistance on railroads under average conditions, and including all forms of resistance, is given by Clark, in pounds per ton, as:

$$\text{For train only, . . } R = 6 + \frac{v^2}{240} \pm 2240i.$$

$$\text{For engine and train, } R = 8 + \frac{v^2}{171} \pm 2240i.$$

$$\text{Where } i = \text{inclination of track} = \frac{h}{5280}.$$

On street railroads the resistances of the cars are greater, and sometimes four times as great, as on railroads. Hughes found on an English "tramway" a resistance of 0.0115, 26 lbs. per ton.

These frictional resistances are sometimes on railroads greatly increased by the resistance of the air, which as "head resistance" amounts—in pounds per square foot of front exposed—to 0.005 of the square of the velocity, in miles per hour, with which the air meets the head of the train. Side-winds often increase the flange-resistance seriously, and thus greatly add to the power required in hauling trains.

Rankine gives* for the resistance of single railroad-carriages *having cylindrical wheels*,

$$R = \left(4\tfrac{1}{2} + \frac{1.4}{r}\right)T,$$

in which R is the resistance in pounds, r is the radius of curvature of the line in miles, and T is the load in tons.

From Gooch's experiments is derived

$$R = [6 + 0.3\,(V - 10)]\;(T + 2\,E);$$

and from Harding and Russell,

$$R = \left(6 + \frac{V}{3}\right)(E + T) + \frac{V^2A}{400};$$

in which last two V is the speed in miles per hour, E the weight of engine in tons, and A is the area of front of train in square feet.†

American trains have on good tracks exhibited much less resistance than is estimated as above.

The following table gives the coefficients of rolling friction; i.e., it gives values of f for the formula $R = f\,\dfrac{W}{r}$, in which R is the resistance, W the total weight, and r is the radius of the wheel or the roller.

* Exper. Inquiry on the Use of Cylindrical Wheels on Railways, 1842.

† App. Mec., p. 620.

Kind of Road.	Value of f. British.	Value of f. Metric.
Newly-laid sand or gravel	0.067	0.045
Stony, in ordinary condition	0.05	0.035
Well-paved	0.02	0.015
Hard, smooth ground	0.02	0.015
Well macadamized and rolled	0.015	0.01
Smooth wooden pavement	0.01	0.007
Ordinary railroads	0.003	0.002
Well-laid railroad-track	0.002	0.0015
Best possible railroad	0.001	0.0007

The resistance of trains running on curves has been studied more recently by Mr. S. Whinery, who deduces for total resistance the following formula:*

$$R = D\frac{(g + l)}{25} + an,$$

in which R is the total resistance, D the degrees of curvature, g the gauge of the track, l the length of rigid wheel-base, and a and n are quantities expressing resistances due to accidental and irregular conditions.

The resistance is inversely as the radius of curvature, directly as the load, and nearly independent of the velocity.

Wellington† makes the following comparison of train-resistances for various methods of lubrication at the speed of ten miles per hour for ordinary work:

	Lbs. per ton.
Tower's experiments, bath of oil	0.278
" " pad or siphon	1.9
Thurston's experiments, light loads	2.75
" " heavy loads	1.75
Wellington's experiments (gravity-tests of cars in service): light loads	6.0
heavy "	3.9
" " direct tests (as shown in Fig. 2)	5 1 / 3.7
Thurston's experiments, inferior oils	4.8 / 3.0
Morin's experiments, continuous lubrication	6.0 to 10.8

* Trans. Am. Soc. C. E., April, 1878.

† Trans. Am. Soc. C. E., 1884.

It is concluded that a minimum resistance is reached usually at a speed between 10 and 15 miles per hour, but that the increase is not usually great at higher speeds where the common system of lubrication is practised. The Author finds evidence that in ordinary work the resistance varies from as low as 4 lbs. per ton of train up to 25, and even sometimes above 30 lbs., per ton.

Chanute* thus analyzes the increase of resistance at 25 miles per hour, when the resistance is increased by curvature about 0.4 lb. per degree and per ton:

Due to twist of wheel	0.001
" slip of wheel	0.1713
" flange-friction	0.2450
" loss at couplings	0.0213
Total	0.4386

Loose wheels reduce this loss 20 or 25 per cent. The rigid form of wheel-base of European cars and locomotives doubles the increase due to curves, as well as increases the resistance on the straight line. The "coning" of wheels somewhat increases the resistance—according to Chanute—from 0.12½ to 0.25 lb. per degree of curve and per ton.

Professor Franck,† studying the earlier experiments of Vuillemin, Guebhard and Dieudonné, and of Rockl, obtains the formula for resistance,

$$w = m - \frac{lFv^2}{Q},$$

in which w is the resistance in kilogrammes per tonne, Q is the weight in tonnes, m, l, and F are coefficients, as follows:

For passenger-engines	$m = 0.0032$
" freight-engines	$m = 0.0038$ to 0.0039
" the cars	$m = 0.0025$
" all cases	$l = 0.1225$
" passenger-engines	$F = 7$
" freight-engines	$F = 8$
" passenger and box cars	$F = 0.5$
" unloaded flat cars	$F = 0.4$
" loaded flat cars	$F = 1.0$

* Trans. Am. Soc. C. E., April, 1878.

† Memoirs de la Société des Ingenieurs Civils, 1883.

He considers that this formula, used with these constants, will allow of very exact calculation of the resistance of trains.

116. Rennie's Experiments on Friction of Solids, usually unlubricated and dry, led to the following conclusions: *

(1) The laws of sliding friction differ with the character of the bodies rubbing together.

(2) The friction of fibrous materials is increased by increased extent of surface and by time of contact, and is diminished by pressure and speed.

(3) With wood, metal, and stones, within the limit of abrasion, friction varies only with the pressure, and is independent of the extent of surface, time of contact, and the velocity.

(4) The limit of abrasion is determined by the hardness of the softer of the two rubbing parts.

(5) Friction is greatest with soft and least with hard materials.

(6) The friction of lubricated surfaces is determined by the nature of the lubricant, rather than by that of the solids themselves.

Experimenting with cloth, Rennie found the resistance to starting to vary with time of rest from one third to even more than the total weight. Increase of surface-area produced great increase in the angle of repose. The following table gives values of the coefficient of *friction of rest* for loads on the metals up to the limit of abrasion, as given by Rennie:

FRICTION OF REST.

PRESSURE.		VALUES OF f.			
Pounds on square inch	Kilogramme on square metre.	Wrought-iron on Wrought-iron.	Wrought on Cast Iron.	Steel on Cast-iron.	Brass on Cast-iron.
186⅔	131.220	0.25	0.28	0.30	0.23
224	157.460	0.27	0.29	0.33	0.22
336	236.200	0.31	0.33	0.35	0.21
448	314.932	0.38	0.37	0.35	0.21
560	393.664	0.41	0.37	0.36	0.23
672	472.396	abraded.	0.38	0.40	0.23
784	551.128	"	abraded.	abraded.	0.23

* Philosophical Transactions, 1829, p. 169.

After abrasion begins, the coefficient rises as the pressure increases. The pressure at which this increase begins to be observable is as low as 8 lbs. per square inch (0.6 kg. per sq. cm.) with pure tin.

Rennie, using tool-steel, found it to abrade at a pressure of 10 tons per square inch (1575 kgs. per sq. cm.). He remarks that the hardening property of steel, and its great power of resisting abrasion, make it superior to all known metals for use in delicate instruments, as in pendulums and balances, where these properties are essential.

The same experimenter, among other researches, determined the friction of ice upon ice, finding it to vary from 12½ per cent. under a pressure of one ounce per square inch (0.0046 kg. per sq. cm.) down to 1⅝ per cent. where the pressure rose to 9 lbs. per square inch (0.6 kg. per sq. cm.) After sixteen hours' contact, the friction was unchanged at the lower limit, but became 4 per cent. under the higher pressure. The friction of steel skates was 4 per cent. at a pressure of 2 lbs. per square inch (0.014 kg. per sq. cm.), but only 1½ per cent. at 200 lbs. per square inch (14 kgs. per sq. cm.)

117. Friction of Brakes and Rails.—The most instructive experiments upon the friction of unlubricated metals under heavy pressures are probably those obtained on railroads by the use of continuous brakes. The data which are perhaps most commonly used in estimating the adhesion of engines are those given in Molesworth's Pocket-Book, which are as follows:

ADHESION PER TON (OF 2240 LBS.) OF LOAD ON THE DRIVING-WHEELS.

When the rails are very dry	0.268 = 600 lbs. per ton.
" " " wet	0.241 = 550 " "
In ordinary English weather	0.200 = 450 " "
In misty weather, if the rails are "greasy"	0.134 = 300 " "
In frosty or snowy weather	0.089 = 200 " "

If these figures are compared with experiment, it will be found that practically a locomotive will, at slow speed and under favorable circumstances, pull a heavier load, and that at high speeds it will not pull as much as the figures show that it should—a consequence of the now ascertained fact that the

resistance is affected by speed, as well as by pressure and by temperature.

A series of experiments were made on the Paris and Lyons Railroad "with a wagon, presumably having four wheels, of which the brake was screwed up, so that the wheels were skidded." The resistance to traction or the friction on the rails, at various velocities, is given as follows by Poirée:

FRICTION OF IRON ON IRON.

EMPTY WAGONS. 3.40 tons.	STATE OF THE RAILS.			
	Dry.	Very Dry	Damp.	Dry and Rusty.
Velocity of wagon / Miles per hour.	Coefficient of Friction. Weight = 1.	Coefficient of Friction. Weight = 1.	Coefficient of Friction. Weight = 1.	Coefficient of Friction. Weight = 1.
9 to 14	0.208	.....	.....	0.201
14 to 18	0.179	0.246	.....	0.182
18 to 20	0.167	.....	0.110	0.175
22 to 23	.....	0.222	.....	0.162
30 to 40	0.144	0.202	.....	.....
40 to 50	.....	0.187	0.083	0.136

From these experiments it will be seen that the friction with a dry rail at a speed of 9 to 14 miles per hour is equal to about one fifth of the load, while at 30 to 40 miles per hour it is about one eighth.*

The following table shows the result obtained by Captain Galton and Mr. Westinghouse by the sliding of the wheel on the rail, that is, steel tires on steel rails:

FRICTION OF STEEL ON STEEL.

AVERAGE SPEED PER HOUR.		COEFFICIENT OF FRICTION: Commencement of experiment to 3 seconds.
Miles.	Kilometres.	
10	17	0.110
15	25	0.087
25	42	0.080
38	60	0.051
45	75	0.047
50	80	0.040

* *Railroad Gazette*, September 20, 1878.

From these two tables it will be seen that the results obtained differ very widely, and that the coefficients given by Poirée are almost twice as great as those given by Captain Galton. In one respect, however, they agreed, which is that the friction diminishes very rapidly as the speed increases.*

By applying the coefficients given in the preceding tables, and calculating the adhesion of locomotive-wheels, we have the following table, in which the coefficients given in the second column of Poirée's table are employed in making the calculation. The coefficient for a speed of 22 to 30 miles per hour and for 40 to 50 miles per hour not being given in this column, the approximate quantities 0.156 and 0.133 have been used in the calculations.

ADHESION PER TON (2240 LBS.) LOAD ON THE DRIVING-WHEELS.

Poirée.		Galton and Westinghouse.	
Speed in miles per hour.	Adhesion.	Speed in miles per hour.	Adhesion.
9 to 14	465.9 lbs. per ton.	10	246.4 lbs. per ton.
14 to 18	400.9 " "	15	194.8 " "
18 to 22	374.0 " "	25	179 2 " "
22 to 30	349.4 " "	38	127.6 " "
30 to 40	322.5 " "	45	114.2 " "
40 to 50	297.9 " "	50	89.6 " "

The results given by Poirée's data at the slow speeds do not differ very widely from the data as given by Molesworth.

The Galton-Westinghouse experiments also show that the friction of brake-shoes on the wheels follows the law that governs the friction of the wheels on the rails.

The following table shows the more important results:†

* *Railroad Gazette*, September 20, 1878.

† *London Engineering*, August 23, 1878.

FRICTION OF BRAKES.

Average Speed.			Coefficient of Friction Between Cast-iron Brake-blocks and Steel Tires of Wheels.			
Per second.	Per hour.					
Feet.	Miles.	Kilom.	1st 3 seconds.	5 to 7 sec.	12 to 16 sec.	24 to 25 sec.
7	5	8	0.360	.....	.....	.....
14	10	17	0.320	0.209	.....	.....
35	20	33	0.205	0.175	0.128	0.070
43	30	50	0.184	0.111	0.098	.....
58	40	70	0.134	0.100	0.080	.....
73	50	85	0.100	0.070	0.056	.....
88	60	100	0.062	0.054	0.048	0.043

The coefficient with wrought-iron shoes at 18 miles (30 kilom.) per hour was 0.170, at 31 miles (50 kilom.) 0.129, at 48 miles (80 kilom.) 0.110; being somewhat less than with cast-iron, but the difference is not very marked.

Captain Galton concludes that "it may be assumed as an axiom that for high velocities a brake is of comparatively small value unless it can bring to bear a high pressure upon the surface of the tire almost instantaneously, and it should be so constructed that the pressure can be reduced in proportion as the speed of the train is reduced, so as to avoid the sliding of the wheels on the rails." *

His conclusions are thus summarized:

(1) The application of brakes, when a "skidding" of the wheels does not occur, does not seem to reduce their rate of rotation.

(2) Skidding occurs immediately when their velocity is reduced below that due to the speed of the train.

(3) Resistance is *reduced* by "skidding" the wheels.

(4) The pressure required to produce skidding is greater than that needed to hold the wheels while skidding.

(5) The pressure of the brake-blocks must be proportional to the coefficient of friction.

The experiments of the British Commission on Accidents, 1877, with the continuous brake, gave, as best results, the following:

* *Railroad Gazette*, 1877.

Weight of engine, tons	35.7
" " tender, "	14.5
" " train, "	13.0
Number of brake-vans	2 0
Weight of loaded train, tons	207.0
Friction of train, per cent	0.40 (?)
" " engine and tender, per cent	0 60 (?)
Resistance by brake, per cent	10.6
Distance, at 60 miles, before stop, feet	1128.0
Time of applying brake, seconds	1.5
" " removing " "	3.0

The length of stop was, approximately, in feet, one ninth the square of the speed in miles per hour. The coefficient of friction between wheel and brake was less as speed increased, varying from about 0.25 at starting to 0.15 at forty miles per hour.

Riveting, in steam boilers and bridge-work, or other constructions, is usually taken as having a coefficient, $f = 0.333$; but it should never be reckoned upon as an element of definite value, although the enormous pressure produced by the shrinkage of heated rivets, while cooling, gives it some importance. The elastic limit of common iron is usually not far from 25,000 lbs. per square inch (1757.5 kgs. per sq. cm.), and one third this amount, above 8000 lbs. (562.4 kgs.) per unit of section of rivet, is a quantity of real value as an element of safety.

118. The Friction of Belts and of Gearing has been often studied experimentally. Morin concluded its amount for belting to be proportional to the angle on the pulley subtended by the belt, to the logarithm of the ratio of tensions, and to be independent of the width of belt and of the linear measure of the arc embraced by it—i.e., independent of the area of contact. He obtained $f = 0.28$ to $f = 0.38$, the value varying with the condition of the belt.

Adopting the formula of Prony for the difference of tension on the two parts of the belt, the values of its coefficient, k, were obtained as in the table.

The maximum difference of tension allowable is

$$D = T_1 - T_2 = (k - 1)T_2.$$

The minimum tension allowable to prevent slip is taken as

$$T_2 = \frac{T_1 + T_2}{2} = \frac{1}{2}\frac{k+1}{k-1}D.$$

VALUE OF k IN PRONY'S FORMULA.

Proportion of Circumference in contact.	New Belt on Wooden Pulleys.	Ordinary on Wood.	Belts on Iron.	Wet Belts on Iron.	Rope on Wooden Axles.	
					Rough.	Smooth.
0.20	1.9	1.8	1.4	1.6	1.9	1.5
0.40	3.5	3.3	2.0	2.6	3.5	2.3
0.60	6.6	5.9	2.9	4.2	6.6	3.5
0.80	12.3	10.6	4.1	6.8	12.3	5.3
1.00	23.1	19.2	5.8	10.9	23.9	8.0
1.50	....	....	....	....	111.3	22.4
2.00	....	....	....	....	535.5	63.2
2.50	....	....	....	....	257.48	178.5

The maximum stress allowable on the leather was stated at about 350 lbs. per square inch of cross-section.

In the equations*

$$R = T_1 - T_2 = T_1(1 - e^{f\theta}) = T_2(e^{f\theta} - 1),$$

$$\frac{T_1 + T_2}{2R} = \frac{e^{f\theta} + 1}{2(e^{f\theta} - 1)},$$

f varies from 0.15 to 0.6, the former value being found only where the belt is actually wet with oil.

Reuleaux takes $f = 0.25$, and the experiments of Messrs. Towne and Briggs† indicate that this value is exceeded, under ordinary working conditions, more than 60 per cent.

Rubber belting has greater adhesion than leather, and values of f may be used exceeding very greatly those adopted for leather.

The angle $\theta = 2\pi n$, where n is the number of turns or part of turns taken by the belt about the pulley. Rankine gives‡ the following values of the coefficient $2.7288f$ in the equation

* Chapter II., § 31.

† *Journal of the Franklin Institute*, 1868.

‡ Machinery and Mill Work, p. 352.

$e^{f\theta} = 10^{2.7288f/n}$ which comes into use in the application of these formulas, as seen in Chapter II.:

$$
\begin{array}{rcccc}
f = & 0.15 & 0.25 & 0.42 & 0.56 \\
2.7288f = & 0.41 & 0.68 & 1.15 & 1.53
\end{array}
$$

and, where $\theta = \pi$ and $n = \frac{1}{2}$, as is usual,

$$
\begin{array}{rcccc}
T_1 \div T_2 = & 1.603 & 2.188 & 3.758 & 5.821 \\
T_1 \div R = & 2.66 & 1.84 & 1.36 & 1.21 \\
(T_1 + T_2) \div 2R = & 2.16 & 1.34 & 0.86 & 0.71
\end{array}
$$

Usually we assume $T_2 = R$; $T_1 = 2R$; $(T_1 + T_2) \div 2R = 1.5$ and f becomes 0.22.

Rankine* gives f for a wire-rope running on cast-iron at 0.15 and on gutta-percha at 0.25.

Clark† gives the following table based on the work of Mr. H. R. Towne, and taking the working stress on the belt at $66\frac{2}{3}$ lbs. per inch in width for single belts.

DRIVING POWER OF LEATHER BELTS.

Arc of Contact.	Stress on the Belt per Inch.	Horse-power Transmitted per Inch in Width.		Sum of Tensions per 1 inch of width.	Pressure on Journals, Pounds per 1 inch of width.
		At 1 ft. per Second, Speed of Belt.	Per ft. Diam. and per Rev. per Minute.		
90°	32 33	0.059	0.00308	101.00	71.42
100°	34.80	0.063	0.00331	98.53	75.47
110°	37.07	0 067	0.00353	96.26	78.85
120°	39 18	0.071	0.00373	94.15	81.53
150°	44.64	0 081	0 00425	88.69	85.67
180°	49.01	0 089	0.00467	84.32	84.32
210°	52.52	0.095	0 00500	80 81	78 05
240°	55 33	0.100	0 00527	78.00	67.59
270°	57.58	0.105	0.00548	75.75	53.56

Rope-gearing has a value of $f = 0.25$ to $f = 0.8$, and the resistance to slipping is increased in proportion to the cosecant of the half-angle of the wedge-shaped groove of the carrying-wheel.‡

* Machinery and Mill Work, p. 352.

† Manual for Mechanical Engineers, p. 750.

‡ *American Machinist*, November 1, 1884.

In Tests of Gearing, by the Author, the following combinations were used: (1) An ordinary worm and wheel, the worm double-threaded, 2-inch pitch: pitch diameter, $6\frac{1}{10}$ inches; length of worm, $4\frac{15}{16}$ inches; the wheel of $15\frac{15}{16}$ inches pitch diameter, $2\frac{1}{2}$ inches face; velocity-ratio, 25 to 1; worm of bronze, wheel of cast-iron. (2) An Albro-Hindley worm and wheel, worm $6\frac{7}{8}$ inches; pitch diameter, 5 inches long; velocity-ratio, 25 to 1; worm and wheel cast-iron. (3) Two pairs of spur-wheels and pinions, the wheels having 80 teeth, "4 pitch," and the pinion 16 teeth, giving a final velocity-ratio of 25 to 1.

The ordinary worm was driven at speeds varying from 41.6 to 337 revolutions per minute, giving speed of gear of 1.66 to 13.43 revolutions. The horse-power transmitted to the gearing ranged from 0.2 to 4.14, and that taken off at the brake from 0.55 to 1 77; efficiency, from 0.268 to 0.458.

The Albro-Hindley worm, under precisely similar circumstances, gave an efficiency ranging from 0.33 to 0.64. In both instances a sperm-oil bath was used for lubrication.

In testing the spur-gearing, the speeds of the driving-pinion were from 36 to 231 revolutions, the horse-power communicated to the train from 0.18 to 2.67; power delivered, from 0.133 to 2.21; efficiency, 0.51 to 0.92.

The efficiency, in the case of the ordinary worm-gearing, increased with the velocity up to 221 feet of rubbing per minute, from which point it decreases as the speed is increased. With the Albro-Hindley worm and wheel the maximum efficiency was found at 243 feet of rubbing per minute. With either form of gearing, the highest efficiency is to be found at a speed of rubbing of the surfaces in contact, which is different with different forms and proportions of gearing. The "Hindley screw" is a more efficient form of worm-gearing than the usually considered standard worm-gear, and the best form of gearing, by far, as respects efficiency of transmission, is the epicycloidal form of spur gearing of the same total velocity-ratio, the loss of power in the last-named being but about one third or one fourth as great as in worm-gearing.

The efficiency increased rapidly within ordinary limits as the load increased, in accordance with the law given in Chapter

VII., and later tests of other special forms of worm-gearing gave efficiencies greatly exceeding the above. The common form of gearing is, however, superior to either of the other devices.

Friction-gearing is usually made by turning grooves in the faces of two pulleys made for the purpose with heavy rims, and so setting them that one may be forced into contact with the other, driving it by the friction of the surfaces thus forced into contact. The angle of the V-grooves so made is usually not far from 5.0°, with breadth to depth as 9 to 1, nearly. The coefficient of friction is about $f = 0.16$; but the pressure adopted is about equal to the effort transmitted. The "pitch" of the grooves is usually from $\frac{1}{4}$ to $\frac{3}{4}$ inches (0.6 to 2 cm.). The lost work is less than with a belt—in some cases by 25 or 30 per cent.

119. The Friction of Pump Pistons has been found by Daubuisson and later experimenters to be proportional to their diameters and to the pressure.

The frictional resistance of hydraulic-press plungers was found by Hicks to be, when in good order and under moderately heavy loads, nearly equal to 5 per cent., divided by the diameter in inches, cupped leather-packing being used; i.e., if the total friction-resistance be called F, the total load W, the diameter d,

$$F = 0.05 \frac{W}{d}, \text{ nearly.}$$

The depth of the collars used as packing and the length of the press-plunger have no sensible effect upon the friction, the resistance due to friction increasing directly as the load or the pressure, and inversely as the diameter of the cylinder. For pressures less than 500 lbs. per square inch (35 kgs. per sq. cm.) the friction rapidly increases with decreasing loads. Good lubrication may decrease this resistance very considerably.

Clark gives, for new leather collars not well lubricated, $F = 0.47dp$, and for good lubrication and old collars $F = 0.31dp$, where p is the intensity of pressure.

Slide-valves of metal, on metal seats, are in steam-engines lubricated by the wet steam which passes them, and are re-

lieved of pressure to a limited extent by the steam which finds its way between the valve and the seat. The value of f varies greatly for this case, but is usually taken as $f = 0.15$; it actually often rises to $f = 0.25$, or even to $f = 0.5$, and valve-stems are often broken. In ordinary working the lowest of the above values is probably quite high enough.

Slide blocks, or bars and guides, in machinery are to be calculated by the principles to be given for other cases of lubricated surfaces. If W is the total load on the piston, P the pressure on the guides, A their area, r the length of crank, l that of the rod, and V the speed of piston,

$$P = W\frac{r}{l}; \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad (1)$$

the mean pressure is

$$P_m = P \frac{0.7854r^2}{\sqrt{l^2 - 0.617r^2}}$$

$$= 0.7854\, P\frac{r}{l}, \text{ nearly}; \quad . \quad . \quad . \quad (2)$$

the work of friction is

$$U = P_m v = 0.7854 Pv\frac{r}{l}; \quad . \quad . \quad . \quad (3)$$

and the heat produced becomes

$$H = \frac{U}{J} = 0.001\ Pv\frac{r}{l}, \text{ nearly}. \quad . \quad (4)$$

120. The Friction of Fluids and of Semi-Fluids, such as gases, liquids, resins, and in some cases earth, follow laws varying greatly from those governing the friction of solids, and these laws have been already stated in Chapter II. The friction of liquids and of gases has been experimentally studied by many distinguished investigators. These researches confirm the principles embodied in the mathematical analysis of the case. The friction of any fluid is found to be independent of the pressure, as first shown by Coulomb, who measured the friction of a rotating disk submerged in water, applying vary-

ing pressures to the surface of the mass, and by many later observers who find the frictional losses of head of fluids traversing pipes, under different pressures, to be the same at the same velocities.

The law that the resistance is, with velocity constant, directly proportional to the area of surface is almost axiomatic; it is fully confirmed by experiment. It is found, however, that where a body moves in a large mass of fluid, the friction of the leading portions of the surface of the moving body causes some motion of the adjacent fluid in its own direction, thus reducing the relative velocity, the velocity of rubbing, from forward aft, and correspondingly reducing the resistance of large bodies, as those of long ships.

Low velocities are found to give variations from the law assumed in the theory, while high velocities more closely accord with that law. This variation is only important for velocities considerably less than one foot (0.31 m.) per second.

The smoothness or roughness of surfaces exposed to fluid-friction has been found to considerably affect this resistance. For all velocities usually met with in engineering, the expression

$$R = fAV^2 = f'DA\frac{V^2}{2g}, \quad U = fAV^2 = f'DA\frac{V^2}{2g},$$

given in Chapter II., may be adopted, where R and U measure the resistance and the work of friction, A is the area of rubbing surface, D the density, V velocity of relative flow.

121. The Flow of Gases is subject to modification by changes consequent upon variation of temperature due to friction, and problems relating to such flow are therefore complicated with calculations of the effect of heat; but where no heat is lost by conduction there is no loss of head by friction, except such slight losses as are due to the imperfectly fluid character of known gases.

The loss of head may be taken as the same as for liquids, and the method of flow is similar. Unwin obtains for air

$$f = 0.005\left(1 + 3.6\frac{1}{d}\right), \quad . \quad . \quad . \quad . \quad . \quad . \quad (1)$$

when d is expressed in inches, and the velocity is 400 feet per second or more, the data being obtained from experiments by M. Arson. Experiments at the St. Gothard tunnel give, for probably rougher surfaces,

$$f = 0.0028\left(1 + \frac{3.6}{d}\right). \quad . \quad . \quad . \quad . \quad . \quad . \quad (1)$$

122. The Friction of Liquids, as affecting the work of the engineer, is always a cause of lost work by resisting the relative motion of the liquid and some solid which is driven through it, as when a ship moves across the ocean, or which constitutes a channel along which the liquid is impelled.

Fluid-friction occurring between the touching surfaces of a solid and a liquid is proportional, according to accepted authorities, to the area of surface of contact and to the density of the fluid, and is found, as already stated, to be *nearly* as the square of the velocity of their relative motion; i.e.,

$$F = \frac{fDAV^2}{2g} = fDAh,$$

in which F is the measure of the resistance when f is the coefficient of fluid-friction, D = the density of the fluid, A = the area of surface of contact, V = the velocity of flow, and g = the measure of gravity = 32.2 feet per second, while h is the head due the velocity, and equal to $\frac{V^2}{2g}$.

For iron pipes, according to Eytelwein,

$$f = 0.0056 + \frac{0.00144}{V};$$

or, according to Weisbach,

$$f = 0.0036 + \frac{0.0043}{\sqrt{V}};$$

and for average value, $f = 0.0064$.

The mean velocity of a stream of water, according to Prony, is

$$v = V\frac{7.71 + V}{10.25 + V}$$

where v is the mean and V the maximum velocity of the stream as measured at the middle thread of its surface; the difference between v and V is due to friction.

In flowing streams, according to Eytelwein,

$$f = 0.00716 + \frac{0.00136}{V};$$

or, according to Weisbach,

$$f = 0.00741 + \frac{0.00023}{V};$$

and an average value is $f = 0.0076$.* The value is somewhat variable.

The method of variation of this friction depends both on the nature of the fluid and on the character of the surrounding solid surfaces. Froude found in salt water, and with surfaces of small area coated with tallow or with shellac varnish, that the resistance to the motion of ships, which in well-formed vessels is principally frictional, varies as $V^{1.85}$; surfaces coated with tinfoil gave $F \propto V^{2.16}$. With surfaces of considerable area, the character of surface seemed comparatively unimportant.

The total loss of head, in any case of friction of water in orifices or pipes, may be taken as a *loss of head* equal to

$$F\frac{V^2}{2g} = F\frac{Q^2}{2gA^2},$$

* Rankine, Applied Mechanics, § 638.

in which

$F = 0.054$ for an orifice in a thin plate;
$F = 0.505$ for an entrance into a pipe from a reservoir;
$F = 0.505 + 0.3 \cos i + 0.23 \cos^2 i$ for a mouthpiece making the angle i with the side of the reservoir.

Q is the quantity of water flowing and A the area of section of the channel.

Where the ajutage has the form of the contracted vein, its cross-section at a distance radius from the side of the reservoir is of a diameter equal to 0.7854 the diameter at the side; in this case the value of F becomes practically zero.

In pipes and conduits, $F = f.\frac{lb}{A}$,

in which expression f has the value already assigned; l, b, and A are, respectively, the length, breadth, and area of cross-section of the stream.

Substituting for $\frac{b}{A}$, its value, the reciprocal of the hydraulic mean depth, $\frac{1}{m} = \frac{b}{A}$, we may write $F = f\frac{l}{m}$.

Friction is somewhat increased by bends and "knees" in pipes; and from Weisbach's experiments are deduced, for smooth bends,

$$F = \frac{i}{180^\circ}\left[0.13 + 1.85\left(\frac{d}{2r}\right)^{\frac{7}{2}}\right],$$

in which i is the angle through which the pipe is bent, r is the radius of the curve, and d is the diameter of the pipe; for knees, i.e., rectangular or abrupt changes of direction, we find

$$F = 0.95 \sin^2 \frac{i}{2} + 2 \sin^4 \frac{i}{2}.$$

The values of f and f' in the expressions for fluid-friction vary with circumstances. The values obtained by Froude and

other experimenters accord well with the following, as given for f and f' in the simpler of the expressions given at the opening of Article 120:

	f.	f'.
Painted iron (Unwin)	0.00489	0.00473
Smooth, painted wood (Beaufoy)	0.00350	0.00339
Iron ships (Rankine)	0.00362	0.00351
Varnished surface (Froude)	0.00258	0 00250
Fine sand (Froude)	0.00418	0.00405
Coarse " "	0.00503	0.00488

The resistance of ships is often expressed by the formula of Rankine,

$$HP = \frac{SV^3}{C},$$

in which S is the area of "augmented surface" in square feet, V the speed in knots per hour, and C a coefficient, which ranges from 20,000 to 25,000 in full to fine vessels. The augmented surface is measured by the product of length, mean wetted girth, and a coefficient of augmentation obtained by taking the sum of unity, four times the mean of the squares of the sines of greatest obliquity of water-lines, and the mean of their fourth powers.

Sudden enlargements and sharp bends often cause serious losses of head and of pressure.

Notches discharge less than the quantity which should pass if no such loss as is above described takes place. For a rectangular notch, the volume discharged is

$$\begin{aligned} Q &= \tfrac{2}{3} cbd \sqrt{2gd}, \\ &= 5.35\, cbd^{\frac{3}{2}}, \end{aligned}$$

in which c is a coefficient usually not far from 0.6, b and d are the breadth of notch and the depth of stream issuing through it. If W is the width of the channel,

$$c = 0.57 + 0.1 \frac{b}{W}, \text{ nearly.}$$

123. **The Friction of Earth** has been the subject of many experiments. The alteration in form and location of any mass of earth by the action of gravity, as has been seen (§ 41), is resisted by both friction and adhesion. Where the latter occurs to any considerable extent, as in clayey soils, a bank may even overhang its base at a measurable angle. Where adhesion is inappreciable, as in dry, sandy soil, the surface assumes a uniform slope at an angle with the horizontal which is the "Angle of Repose," the tangent of which measures the "Coefficient of Friction." The latter is also the limit of declivity assumed by any soil or earth in which, as is always liable to be the case, adhesion is destroyed by moisture or other cause. In calculations relating to the sustaining power of earth under foundations or the pressure upon a retaining-wall, the angle of repose, as obtained by direct experiment, must be known to insure safety.

The angle of repose is in some cases liable to be reduced to a very small value by the presence of water, as in flooded quicksand or in saturated clayey earth. The least probable value should in such cases be assumed. In some cases the soil should be considered as a perfectly fluid mass of maximum density, and its pressure calculated as if it were a liquid.

Calling φ the angle of repose, experiment gives the following values of φ and of f, the coefficient of friction, as obtained by Morin:

MATERIAL.	ϕ	f	$\frac{1}{f}$
Stone and brick	30° to 35°	0.6 to 0.7	1.7 to 1.4
Same on clay (dry)	27°	0.50	2.0
" " " (wet)	18°	0.33	3.0
Earth	15° to 45°	0.25 to 1.00	1.0 to 4.0
Sand and Gravel	40° to 48°	0.8 to 1.1	0.9 to 1.2
Clay (wet)	18°	0.33	3.0
" (damp)	45°	1.0	1.0

The following are values of the factors used in the equations of Chapter II., § 41, corresponding to several values of φ. The quantities in line (6) are especially interesting, as applying to foundations and to retaining-walls subject to jar or action of frost.

VALUES OF ABOVE QUANTITIES.

		$\phi =$ 0°	15°	30°	45°	60°
(1)	$f = \tan\varphi$	= 0	0.268	0.577	1.000	1.732
(2)	$\frac{1}{f} = \cot\varphi$	= ∞	3.732	1.732	1.000	0.577
(3)	$\sin\varphi$	= 0	0.259	0.500	0.707	0.866
(4)	$\frac{1+\sin\varphi}{1-\sin\varphi}$	= 1	1.700	3.000	5.826	13.924
(5)	$\left(\frac{1+\sin\varphi}{1-\sin\varphi}\right)^2$	= 1	2.890	9.000	33.94	193.8
(6)	$\frac{1+\sin^2\varphi}{(1-\sin\varphi)^2}$	= 1	1.945	5.000	17.47	97.4
(7)	$\frac{\sin\varphi}{3(1+\sin^2\varphi)}$	= 0	0.081	0.133	0.157	0.165

The friction of earth on the pneumatic tubes used in laying foundations of bridges is given by Schmoll as below:

MATERIAL OF TUBE.	SOIL.	DRY.		WET.	
		Start.	Motion.	Start.	Motion.
Sheet-iron, unriveted	Gravel and sand.	.402	.458	.335	.441
" " riveted	" " "	.397	.491	.468	.548
Cast-iron, rough	" " "	.368	.467	.365	.497
Granite, hammered	" " "	.427	.537	.410	.480
Pine, sawn	" " "	.409	.511	.411	.499
Sheet-iron, unriveted	Sand.	.536	.631	.366	.325
" " riveted	"	.727	.839	.516	.498
Cast-iron	"	.564	.606	.474	.370
Granite	"	.647	.700	.473	.529
Pine	"	.663	.734	.579	.479

The friction of rest is here less than that of motion. It is not known whether this is a general rule for friction of this character, or due to circumstances peculiar to these experiments; it is probably a case of fluid-friction, however, and that being the fact should follow its laws. It is well known that a load which will force an ordinary pile through soft bottom will not start it again if it is once stopped and the earth allowed to settle about it.

It is advised by Trautwine that retaining-walls be given a thickness of from one third to one half their height ordinarily, accordingly as they are built of rubble and mortar or cement, or are built up dry, thus giving a factor of safety when the usual theory is adopted of from 7 to 20, asserting that a factor of

safety of two is too small. The assumption introduced into the theory, by the Author, that the effect of friction may be the increase of pressure, instead of a decrease, permits the use of a reasonable factor; two may be used, four would be better.

The maximum pressure allowable on foundations in earth is considered usually to be one or two tons, and in very compact soil sometimes four or six tons per square foot. Clay should carry from one to two tons. Uniform pressure should be secured if possible.

124. **Mixed Friction**, or "mediate friction," as defined in Chapter II., arising from the resistance of solids in contact conjoined with the resistance of fluids to relative motion, has been frequently made a subject of investigation; but it has rarely occurred that the bearing of the two methods of resistance upon each other and their resultant effect have been noted. Where the thickness of fluid interposed between two solids is great, as when a ship is under way in deep water, the resistance follows the laws of friction of fluids; when the two solids are near each other, as when a vessel moves over shoals, the law begins to change; and when they are in close proximity, as in the case of lubricated sliding or rotating pieces, the law becomes much more in accordance with that of friction of solids.

Recent experimentors upon the friction of machinery have begun to note these variations. The total resistance in such cases is found by experiment to be a function of pressure, velocity, and temperature.

When the rubbing-surfaces become dry, the variable part of these functions disappear and the law is reduced to that of friction of solids.

125. **The Friction of Lubricated Surfaces** was made a subject of experiment by both Rennie and Morin, as well as by many later investigators. Their results are of comparatively little value, however, in consequence of the fact that it was unknown until recently that the friction in such cases is greatly influenced by pressures, velocities, and temperatures, and because of the fact also that the experiments included but a limited range of conditions, and those were only such as are not most common in engineering.

Morin observed the great difference between the friction of rest and that of motion, and attributed this difference to the expulsion of the lubricant when the rubbing surfaces were relatively at rest. He thus accounted for the comparatively great effort required to start machinery into motion.

The following table presents the values of the coefficients of sliding friction measured by Morin, and the friction-angles corresponding to them, as determined for various conditions of surface:

SLIDING FRICTION OF SOLIDS.

Material.	Condition of Surfaces.	f.	Friction Angle.
Brick on limestone	Dry	0.67	33° 50′
Cast-iron on cast-iron	Slightly greased.	0.16	9° 6′
" on oak	Wet	0.65	33° 2
Copper on oak		0.17	9° 38′
" " "	Greased	0.11	6° 17′
Leather on cast-iron		0.28	15° 39′
" " "	Wet	0.38	20° 49′
" " "	Oiled	0.12	6° 51′
" " oak	Fibres parallel	0.74	36° 30′
" " "	" crossed	0.47	25° 11′
Oak on oak	" parallel, dry	0.62	31° 48′
" "	" crossed, dry	0.54	28° 22′
" "	" parallel, soaped	0.44	23° 45′
" "	" crossed, wet	0.71	35° 23′
" "	" end to side, dry	0.43	23° 16′
" "	" parallel, greased	0.07	4° 6′
" "	Heavily loaded and greased.	0.15	8° 45′
Oak on pine	Fibres parallel	0.67	33° 50′
" limestone	" on end	0.63	32° 15′
" hempen cord	" parallel	0.80	38° 40′
Pine on pine	" "	0.56	29° 15′
" oak	" "	0.53	27° 56
Smooth granite on rough granite		0.66	33° 26′
Stone on dry clay		0.51	27° 2′
" wet clay		0.34	18° 47′
Wrought-iron on oak		0.62	31° 48′
" "	Wet	0.65	33° 2′
" on wrought iron		0.28	15° 39′
" " cast-iron		0.19	10° 46′
" " limestone		0.49	26° 7′
Wood on metal	Greased	0.10	6° 0′
" " smooth stone	Dry	0.58	30° 7′
" " " earth	"	0.33	18° 16′

These values are so greatly affected by variation of pressure, temperature, and velocity of rubbing, that this table has comparatively little value. More complete and useful tables will be given later.

126. **The Friction of Journals** variously lubricated was made a subject of investigation by Rennie and by Morin, and has recently been experimentally studied by many engineers. The following are principally Morin's figures as obtained with journals of from 2 to 4 inches (5 to 10 cm.) diameter, and loaded with from 330 lbs. (150 kgs.) to 2 tons (or tonnes). The resistances were measured with a Morin recording dynamometer. The results are considered to be somewhat uncertain. As will be seen later, very much better conditions are probably attained in good practice with ordinary machinery. The values of f here given may be taken as fair figures for new journals lightly loaded. More extensive and more exact and useful determinations will be given in succeeding pages. Those here given are so greatly modified, as stated in the preceding article, by variations of speed, pressure, and temperature, that they cannot be taken as correct for general purposes.

FRICTION OF JOURNALS.

Material.	Unguent.	Lubrication.	
		Intermittent.	Continuous.
Cast-iron on cast-iron	Oil, lard, tallow	0.07 to 0.08	0.03 to 0.054
	Oil and water	0.08	
	Asphalt	0.054	
	Unctuous	0.14	
	" and wet	0.14	
Cast-iron on bronze	Oil, lard, tallow	0.07 to 0.08	0.03 to 0.054
	Unctuous	0.16	
	" and wet	0.16	
	" (slightly)	0.19	*
	Dry	0.18	†
Cast-iron on lignum-vitæ	Oil, lard	....	0.090
	Unctuous (oil or lard)	0.10	
	" (lard and graphite)	0.14	
Wrought-iron on cast-iron	Oil, lard, tallow	0.07 to 0.08	0.030 to 0.054
Wrought-iron on bronze	Oil, tallow, lard	0.07 to 0.08	0.030 to 0.054
	Unctuous and wet	0.19	
	" (slightly)	0.25	‡
Iron on lignum-vitæ	Oil, lard	0.11	
	Unctuous	0.19	
Bronze on bronze	Olive-oil	0.10	
	Lard	0.09	
Bronze on cast-iron	Oil, tallow	....	0.030 to 0.054
Lignum-vitæ on cast-iron	Lard	0.12	
	Unctuous	0.15	
Lignum-vitæ on lignum-vitæ	Lard	....	0.07

* Wear began. † Wood slightly greasy. ‡ Wear commenced.

A large number of determinations, made under conditions more precisely defined and under circumstances more exactly accordant with those of everyday practice, will be given hereafter. It will be seen by reference to the theory of journals, that the resistance depends upon the method of fitting. It is, however, usually taken as $F = fP$, as for a journal fitting on a line.

The value of f on *grindstones* has been found by Dr. Hartig to vary from $f = 0.20$ or $f = 0.30$ to $f = 0.70$ to $f = 1.0$ for light work and high speed and heavy work and slow speeds, respectively.

Tests made on the machine of the Lake Shore and Michigan Southern Railway, and reported to the Master Mechanics' Association, are stated to have given the following results: *

Fifty drops of each oil were used at one application, and the machine was driven at a speed corresponding to 35 miles an hour, until the temperature shown by the thermometer rose from 60° to 200° F. (16° to 93° C.). The total number of revolutions was as follows:

ENDURANCE OF OILS—L. S. & M. S. RR.

Castor	12 946 rev.	West Va.	7,915 rev.
Paraffine	11,685 "	Sperm	7,912 "
Mecca (black)	9,982 "	Tallow	7,794 "
Neat's-foot	8,277 "	Lard	7,377 "

The most extended series of experiments of this character, and in some respects the most valuable obtained in this way, are those of Mr. A. H. Van Cleve.† The test-journal was 7 inches long and 6 inches in diameter (17 cm. × 14 cm.), running in brass bearings, and driven by a 5-horse-power engine. The pressure was applied by a system of scale-beams, and the speed determined by a counter. The temperature was kept at from 96° to 100° F. (36° to 38° C.), and was shown by a thermometer inserted in the bearing. A record was kept of the pressure, the speed, the quantity of oil used, and the power demanded

* *National Car-Builder*, 1877.

† *Scientific American*, December 9, 1871.

to turn the shaft. In a second series of tests, a journal was used 6 inches long and 2⅜ inches in diameter (14 × 6 cm.)

The results indicated that, in general, winter sperm sustains high pressures best; that the mineral oils used only kept the journal equally cool when from 2 to 5 times as much oil was used as of sperm.* The pressure admissible varied nearly inversely as the velocity of rubbing, and the consumption of oil varied in a similar direct ratio. These experiments occupied fourteen months. The following table gives the principal facts:

FRICTION OF 7' × 6' JOURNAL. (VAN CLEVE.)

OIL.	H. P.	Rev. per M.	Pressure. lbs.	Temperature. F.	Gills of Oil. Per Hr.	Relative Value.
Winter Sperm......	3.24 to 3.55	125 to 131	7,000 to 7.500	96° to 98°	0.68 to 0.82	1.00 to 0.91
½ Sperm—½ Lard......	2.45	129	5.260	97°	0.84	0.69
⅔ " —⅓ "	2.61	129	5.600	97°	0.86	0.71
⅓ " —⅔ "	2.15	132	4.500	96°	0.76	0.60
CAR-AXLE BEARING, 6' × 2⅜'.						
Winter Sperm........	3.18	251	7,000	95°	0.25	0.91
LOCOMOTIVE AXLE.						
Winter Sperm........	....	130	7,000	97°	0.40	....
" "	....	100	7,200	94°	0.26	....
" "	....	70	8,000	94°	0.18	....
" "	....	60	9,800	94°	0.14	...
" "	....	130	7.500	98°	0.36	....
" "	....	100	7.500	96°	0.25	....
" "	....	70	8,000	91°	0.19	....
" "	....	60	9.500	90°	0.10	....
Lard................	....	130	4.000	78°	0.31	....
"	....	100	5,200	75°	0.18	....
"	....	70	5.500	73°	0.12	....

As early as 1831 Nicholas Wood determined the coefficient of friction on old, well-worn axles, under conditions not fully specified, to be much less than those given in the table, as obtained by Morin, falling to about 0.02. Later German experiments, with pressures of 200 to 250 lbs. per square inch, gave, at 230 revolutions, $f = 0.00891$ to $f = 0.013$, and it was

* A conclusion which is not true of all mineral oils.

concluded that these values could be reduced. Still later experiments showed an increase of resistance in higher ratio than increase of load, and an increase with increase of velocity, while experiments at Hanover lead to the conclusion that, under loads of from 320 to 1250 lbs. (145 to 564 kgs.) on the journal, the coefficient for iron axles lubricated with rape-seed oil and running in white-metal bearings is 0.009 to 0.0099; that with gun-bronze bearings the figure becomes 0.014; that the value may be taken as independent of the weight of load within usual limits; that the area of the journal does not sensibly affect the resistance; that resistance is practically independent of velocity of rubbing; that grease gives a higher figure than oil for light loads, but the same under heavy loads.* As will be seen by the study of more complete results of experiment to be given later, these conclusions require some important modification. More correct values of f will be given in Chap. VII. Kirschweger obtained for railway axles running in Babbitt metal, $f = 0.009$, and in bronze, $f = 0.014$. Bokelberg and Welkner obtained $f = 0.003$ to $f = 0.013$ for low pressures and velocities and for high pressures and speeds respectively, gun-bronze giving the best results.

The frictional resistance of mill-shafting has been determined by the very numerous and extended experiments of Mr. Samuel Webber. The pressures are here not very high, and Webber's values for the coefficient of friction average very nearly the same as the figures obtained by Morin. They are, for intermittent lubrication, 0.066, and for continuous oiling, 0.044. Morin obtained 0.075 and 0.042.

We may, as shown by analysis, adopt the following formulas for work of friction, U, and horse-power, H.P., required:

$$U = fWS, \text{ on flat surfaces; } \quad (1)$$
$$= 0.26fWdR, \text{ on journals; } \quad (2)$$
$$= 0.175fWdR, \text{ on cylindrical pivots; } \quad (3)$$
$$= 0.026fWdR \operatorname{cosec} \alpha, \text{ on conical pivots; } \quad (4)$$
$$= 0.175fWdR \sec \alpha, \text{ on conical journals. } \quad (5)$$

* W. R. Browne, *Railroad Gazette*, August 16, 1878.

And

$$\begin{aligned} \text{H.P.} &= 0.00003 fWv, \text{ on flat surfaces; } \quad \ldots \ldots & (6) \\ &= 0.000008 fWdR, \text{ on cylindrical journals; } \ldots & (7) \\ &= 0.000005 fWdR, \text{ on cylindrical pivots; } \ldots & (8) \\ &= 0.000008 fWdR \sec\alpha, \text{ on coned journals; } \ldots & (9) \\ &= 0.000005 fWdR \operatorname{cosec}\alpha, \text{ on coned pivots. } \; . & (10) \end{aligned}$$

Mr. D. K. Clark * takes the values of f, from various sources, as averaging $f = 0.07$ and $f = 0.043$, for cases of ordinary and of free lubrication respectively, and thus gets

$$\begin{aligned} U &= 0.0182 WdR, \text{ for ordinary oiling; } \ldots & (11) \\ &= 0.0112 WdR, \text{ for continuous oiling; } \ldots & (12) \\ \text{H.P.} &= 0.0000005 WdR, \text{ for ordinary oiling; } \ldots & (13) \\ &= 0.00000033 WdR, \text{ for continuous oiling; } \; . & (14) \end{aligned}$$

the free supply giving a gain of 40 per cent. In these equations, W is the load in pounds, S the space in feet, R the revolutions per minute, d the diameter in inches, α the angle of the cone.

127. The Size of Journals has been seen (Chap. II., Art. 29) to be determined by the magnitude of the friction, only as to its length. The diameter is made sufficient to insure safety against springing and permanent distortion, and the length is determined by the limit of intensity of pressure allowable; while this limit is fixed, as will be seen more clearly hereafter, by the speed of rubbing and the temperature of the surfaces in contact. The usual maximum pressures, the pressure at which the limit of safety against abrasion is approached, has been given as 500 or 600 lbs. per square inch (35 to 42 kgs. per sq. cm.) for iron crank-pin journals, and as about double these figures for steel. It is, however, variable with change of speed, etc. The maximum pressure on timber, as on the launching-ways of vessels, is below one tenth that for iron. All bearing-surfaces should have sufficient area at least to reduce the intensity of pressure below these figures, and should be increased beyond this extent in the manner given below, with

* Manual, p. 763.

increase of speed, or for journals subjected to unintermitted pressure.

The two surfaces usually differ—the one being hard enough to bear the maximum pressure without change of form, and the other being less hard, in order that it may not abrade the first. With such an arrangement, the surfaces, if properly cared for, take a fine smooth, mirror-like polish, and give a minimum frictional resistance. Cast-iron surfaces are usually less satisfactory than good wrought-iron, although where the areas can be made large, cast-iron bearings work very satisfactorily, and homogeneous and moderately hard steel is vastly better for journals than iron. A pressure of 800 lbs. to the square inch (56 kgs. per sq. cm.) can rarely be attained on wrought-iron at even low speeds, while 1200 lbs. (85 kgs. per sq. cm.) is not infrequently adopted on the steel crank-pins of steamboat engines; but double this pressure has been reached on locomotives, at the instant of taking steam. Seven to nine thousand pounds pressure per inch is reached on the slow-working and rarely moved pivots of swing-bridges. In practice with heavy machinery, higher pressure than 600 and 1000 lbs. per inch (42 to 70 kgs. per sq. cm.) on iron and on steel are rarely adopted, and in general practice we make the pressure less as the speed is greater, since the amount of heat developed is directly a measure of the amount of work done in overcoming friction, and is proportional to the speed as well as to the pressure. Reciprocating motion in journals compels the adoption of greater length than continuous revolution. Slowly moving journals are often but one diameter in length; fast-working journals are sometimes 6 and 8 diameters long. Under steady pressure, this length must be greater than under intermitted loads.

By watching the behavior of the journals of the engines of naval steamers in 1862, the author determined the following formula for the size of journals for such engines and for stationary steam-engines:*

$$l = \frac{PV}{60,000d},$$

* Materials of Eng., vol. i.

in which l is the length of the journal in inches, P the average load in pounds, and V the velocity of rubbing in feet per minute; d is the diameter in inches. Rankine published, in 1865, the following as applicable to locomotive practice:

$$l = \frac{P(V + 20)}{44,800d}.$$

These are intended for iron journals; those of steel may sometimes work well if of one half the length given by the formulas.

The length being known, the mean pressure per square inch admissible is within the limits above given,

$$p = \frac{60,000}{V} \quad \text{(Thurston).}$$

$$p = \frac{44,800}{V + 20} \quad \text{(Rankine).}$$

Where journals are exposed to dust, as in locomotives, or to unintermitted pressure, it is advisable to make them of greater length than where they are fully protected. This difference is observed in the two formulas just given. The best makers of mill-shafting make the journals about four diameters long.

The expressions above given can only be taken as correct for such cases as are familiar to the engineer as representing good current practice. They are subject to great variation, with variation of condition and kind of surface, temperature, nature of the lubricant, etc., etc.

For rapidly revolving pivots, lower pressures and correspondingly increased areas of surface must be usually adopted. Fairbairn would restrict pressures, in this case, to less than 240 lbs. per square inch (18 kgs. per sq. cm.), which he thinks a critical pressure. Trautwine takes pressures 40 per cent. lower for iron "steps," and 25 per cent. higher for steel—both to be used for general mill-work. Railway turntable-pivots, and those of drawbridges, which turn exceedingly slowly, sometimes work under pressures approaching the elastic

limit of the metal. Chilled iron and hardened steel work well if properly cared for, under loads of 6000 lbs. per square inch (422 kgs. per sq. cm.) when kept well lubricated.

In all these cases ordinary methods of oiling are assumed. Where the oiling is intermittent, the pressure intermitted, the speed of rubbing small, and the lubricant fluid, these limits should never be exceeded; if, on the other hand, the lubrication is very free, as with the oil-bath, the pressure intermitted or reversed, as on crank pins, the speed of rotation of journal high enough to force the lubricant between the surfaces, and the latter at the same time of good "body," much higher limiting pressures may be sometimes attained. A steady, unintermitted pressure will not permit maximum intensity of pressure to be maintained.

The experiments at the Brooklyn Navy Yard, made under the direction of the Bureau of Steam Engineering, and under these conditions, were reported to indicate the following limits of pressure for a velocity of rubbing of about 200 feet (60 m.) per minute, and a temperature of 116° F. (47° C.), the pressure and speed being unintermitted.

OIL.	PRESSURE. Lbs. per sq. in.	PRESSURE. Kgs. per sq. cm.	OIL.	PRESSURE. Lbs. per sq. in.	PRESSURE. Kgs. per sq. cm.
Summer Sperm Oil	86	6	Heavy Mineral Oil	73	5 I
Winter Sperm Oil	70	5	Light Mineral Oil	65	4.5
Winter Lard Oil	62	4.3	Paraffine Oil	55	4
Tallow Oil	50	3.5	Mineral and Fish Oil	48	3.5

These figures are very much smaller than would be given by either of the rules above given, which at 200 feet would be from 200 to 300 lbs. per square inch (14 to 21 kgs. per sq. cm.). In other words, the apparent factor of safety is here at least 2 or 3 for the best oils. The rules reduced to this basis would read

$$p = \frac{15000}{V}, \text{ nearly,}$$

for sperm-oil. As previously given, however, they have been adopted in the design of many steam-engines and other machines, and have given satisfactory results. The adoption

of the latter will give good results for light machinery, but would produce journals of impracticable size if used for heavy work.

The pressure at which the film of oil is displaced and the friction becomes altered from liquid friction to mixed, or "mediate," friction by contact of the metals, varies greatly with different oils and at different speeds, and is not exactly known for any one lubricant. These pressures are perhaps not far different from those last given. Mr. C. N. Waite supposes this point to be reached with a pressure of about 84 lbs. per square inch (6 kgs. per sq. cm. nearly) with neat's-foot oil, one half this figure with lard, 70 lbs. (5 kgs.) with sperm, and deduces the conclusion that a light paraffine-oil is best for low pressures and a heavy mineral oil for heavy loads. This point varies, however, very greatly with velocity of rubbing, becoming as a rule greater as the speed increases. It is also, as already stated, very much greater where the pressure is intermitted, as on crank-pins of steam-engines, and less with vibrating journals, as on the "beam-centres" of engines having "working-beams."

128. Machines for Testing Lubricants are used in the most important of all the tests to be applied to determine the precise value of a lubricating material, and in that which most completely and satisfactorily reveals that value, the machine being specially constructed for the purpose.

In order to determine precisely what oils are adapted to any special purpose, or to ascertain for what uses any oil is best fitted, it is necessary to make an examination of the lubricant while it is working under the specified conditions. That is to say: The oil should be put upon a journal of the character of that on which it is proposed to use it, and, subjecting it to the pressure proposed, running it at the speed that the journal is expected to attain; its behavior will then show conclusively its adaptability to such an application. While running, it is necessary to measure the friction produced, and to determine its coefficient, which, as we have seen, is its measure, as well as to be able to note its durability and the rise in temperature of the bearing. These qualities being determined and recorded, all is known of the oil that is needed to determine its lubricat-

ing power, and its value for the purpose intended. A number of such machines have been invented, although but two or three are in use.

One of the oldest is that of McNaught. It consists of two disks. The upper one is loose; the lower one is turned by a pulley on its spindle. The oil is interposed between the disks, and the friction causes a tendency on the part of the loose disk to turn with the other. This tendency is resisted by a pin on its upper side coming in contact with the short arm of a bell-crank lever, the long horizontal arm of which carries a weight which can be adjusted to measure the friction.

The oil to be tested is placed between these two disks. As the lower one turns, the friction between them carries the upper one with it, but its motion is restrained by a pin, which comes in contact with another pin, in the end of the arm of a T-lever. A movable weight slides on the arm, on which is a scale to note its position. A counterweight is attached to the opposite end of the lever, so as to afford the means of a more delicate adjustment. It is evident that the resistance due to the friction between the two disks may in this way be very readily measured by the position of the weight.

Napier's machine consists of a wheel, of which the smooth, wide rim is pressed by a brake-block, which is forced against it with any desired amount of pressure by the action of weighted levers. The effort of the wheel to carry the block around is resisted by another weighted lever, and by it the friction is measured, as in the later machine of Riehlé.

The machine of Messrs. Ingham & Stapfer consists of a shaft running in two bearings and carrying a third journal between them. This latter has adjustable bearings, which are set up to any desired pressure by weighted levers. A thermometer in the top brass enables the heating of the bearing to be observed. A later modification of this machine is seen in that of Ashcroft. In this machine the friction cannot be measured; but the durability of an oil and its effectiveness in keeping a bearing cool can be observed. A somewhat similar but much larger machine has been used at the Brooklyn Navy Yard several years.

The work done on the Ingham & Stapfer machine is sometimes plotted as in the accompanying diagram:

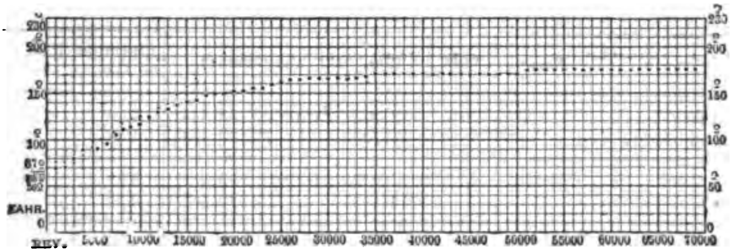

FIG. 36.—OIL TEST. HEAT AND WORK.

The two dotted lines show the behavior of two different samples of oil under test. The line of large dots shows an excellent quality of prepared and purified sperm, that, starting at a temperature of 67° F. (19°.5 C.), has with 70,000 revolutions only attained 176° (80° C.); while the other, an indifferent mixed oil, attains 200° (93°.3 C.) with only 19,000 revolutions. By means of such a diagram a permanent record of all tests can be kept for future guidance.

The value of the lubricant is assumed (improperly) in the use of this machine to be determinable simply by observing its durability and its effect upon the thermometer. In making experiments of this kind, Mr. W. H. Bailey proposes that all should begin at the same standard temperature—say 60° F.—and should terminate at the same point, which he would make 200°. He enters the data, as obtained, on a record-sheet thus arranged:

NAME OF OIL.	Price.	Total Rev. to 200° F.	Temp. of Atmosphere.	Rev. per Degree.

In a test thus made to determine the gumming of oils, Wheeldon obtained the following table:*

* Lecture by Mr. W. H. Bailey, Manchester, G. B.

TESTS OF OIL ON BAILEY'S MACHINE.

Resistance to Oxidation. (*Wheeldon.*)

	Name.	Price.	Rev.	Temperature.	Elevation of Temp.	Rev. per Degree.
First day[1].......	No. 1 Ox.	5/6	13,005	From 80° to 200°	120°	108
Second day[2]....	"		11,787	" 78° to 200°	122°	97
First day[3].......	Sperm.	9/0	16,044	From 65° to 200°	135°	119
Second day[4]....	"		13,104	" 62° to 200°	138°	95
First day[5].......	Mineral(?)	3/6	11,831	From 65° to 200°	135°	88
Second day[6]....	"		......	....	....	..

[1] First trial; new oil. [2] No fresh oil added. [3] First trial; new oil. [4] No fresh oil added. [5] First trial. [6] Second trial; after standing 24 hours the bearings were found glued to the test journal, and the machine refused to start.

The last of these trials could not have been made with an oil of the kind indicated by the name given. Mineral oils do not gum; this was undoubtedly a mixed oil of poor quality.

The *Zeitschrift deutcher Ingénieure*, 1871, gives the following:

Oil.	Price per cwt.	Rev.	Relative Cost.
Refined Rape seed............	$11 25	69 975	100
Mineral......................	7 50	41.850	111.4
Impure Rape-seed............	9 60	26 392	225.9

Lieut. Metcalfe, of the Ordnance Corps, U. S. A., in experiments made at the Frankford Arsenal* in 1873, on axle and trunnion friction, has adopted Rankine's method† of noting the time required by a fly-wheel running loosely on a shaft to lose a given quantity of energy while stopping under the opposing efforts of its own inertia and the frictional resistance of its lubricated bearing on the stationary axle. From this he deduced the coefficient of friction thus:

The energy thus destroyed is

$$U = \frac{Mk^2}{2}a^2,$$

* Ordnance Notes No. LXXXIV. Washington, July 15, 1878.

† Machinery and Millwork, p. 397.

in which M is the mass $\left(\frac{W}{g}\right)$ of the wheel, k its radius of gyration, and a is the initial angular velocity.

The work of resistance by friction is $U' = U$, and is measured by

$$U' = 2F\pi rn = \frac{Mk^2}{2}a^2 .$$

and

$$F = \frac{Mk^2a^2}{4\pi rn},$$

in which F is the effort of friction resisting motion, r the radius of the shaft or journal, and n the total number of revolutions made while stopping. The mean velocity a' is one half the initial velocity a. Then

$$F = \frac{Mk^2a^2}{4\pi rn} = \frac{4Mk^2\pi n}{t^2},$$

where t is the time of retardation in seconds.

$$f = \frac{F}{W} = \frac{F}{Mg} = \frac{4k^2\pi n}{rt^2g} = C\frac{n}{t^2},$$

in which last expression C is a constant to be determined for any wheel used.

In Metcalfe's experiments the pressure was about 100 lbs. per square inch (7 kgs. per sq. cm.), and whale-oil gave $f = 0.015$ to $f = 0.016$, sperm-oil, 0.088; castor-oil, 0.028; axle-grease, 0.030.

The average revolutions were 53 per minute.

This affords a very convenient method of comparing the values of lubricants used upon the wheels of vehicles; the wheel itself may be used as the storer and restorer of the energy expended in friction.

129. The Ashcroft and Woodbury, the Wellington, the Tower, and the Riehlé Machines for testing oils are improvements upon the earlier testing-machines. All embody provisions for ascertaining the value of the coefficient of friction.

The Ashcroft machine is a modified Ingham & Stapfer instrument, as seen in Fig. 37.

It is operated in the same manner. The illustration shows the test-arbor, weighted lever producing pressure, the thermometer indicating changes of temperature, and a dial showing the friction-resistance. The oils tested are compared by noting the rise of temperature during test as already described,

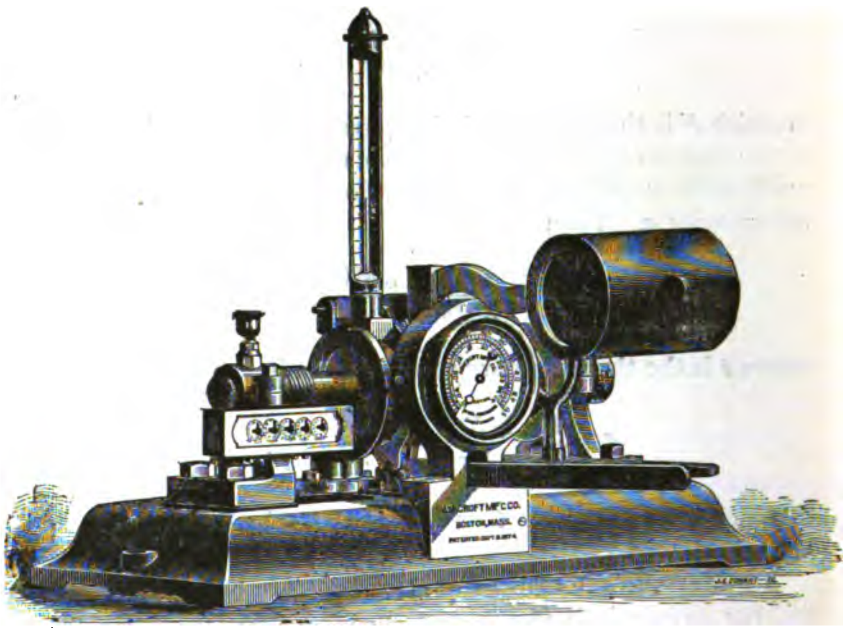

FIG. 37.—ASHCROFT OIL MACHINE.

the maximum allowed being taken usually at a little below the boiling-point of water.

Mr. Woodbury has improved the Nasmyth machine.*

The machine is shown in perspective in Fig. 38.

The lower disk is secured upon the top of an upright shaft, its top being an annulus, ground to a true plane surface. Upon this rests the upper disk, which is a hollow ring of hard composition.

* Trans. Am. Soc. Mech. Engrs., vol. vi., November, 1884.

A partition divides the interior of the hollow ring forming the upper disk, and water can be introduced through the con-

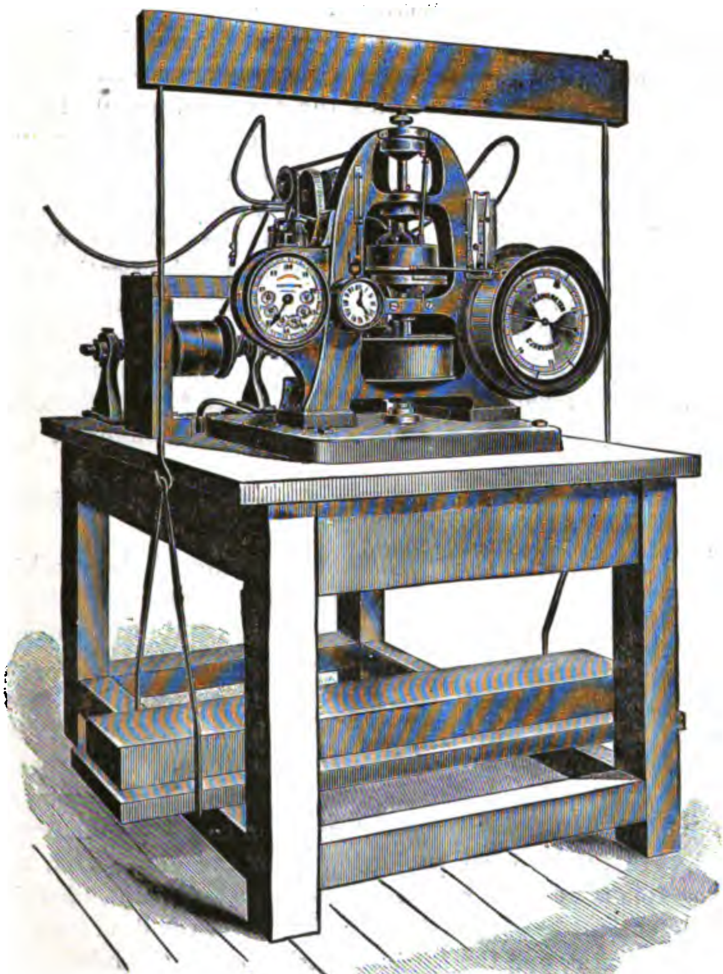

FIG. 38.—THE WOODBURY MACHINE.

necting tubes to control the temperature of the disks or to retain the heat of friction. The sides and top of the upper disk are surrounded by a case of hard rubber, and the space is filled with eider-down.

Ice-water is used to reduce the temperature of the disks to nearly the freezing-point of water, and the friction is noted at each degree of rise in temperature.

A tube of thin copper, closed at the bottom, reaches through to the bottom of the disk, and a thermometer with its bulb placed within this tube indicates the temperature of the friction-surface. A tube leading through the upper disk conducts the lubricant under trial to a recess in the middle of the lower disk. The upper end of this tube, being of glass, exhibits the supply and rate of feeding of the oil. As the friction of a journal depends quite largely upon the method of lubrication, uniformity in the manner of supply is of the utmost importance.

The axes of the upper and lower spindle do not coincide, but are on parallel lines about one eighth of an inch from each other. This prevents the surfaces from wearing in rings, because the same points are not continuously brought in contact with each other.

A counter records the number of revolutions made during any given time.

The dynamometer on the right-hand side of the machine consists of segments and pinions multiplying the deflection of a steel bar, and indicating the stress necessary to produce such deflection by the position of the hand on the dial. When the machine is in operation the lower disk is revolved, and tends to carry the upper disk around with it, by a force equal to the friction due to the lubricant between the disks.

The frictional resistance is thus obtained: The reading on the dynamometer indicates the force of a couple whose arm is the length of the lever projecting from the upper disk, and this couple is opposed by a couple of equal moment, of which the dimensions of the frictional surface form the data for computing the arm, and the frictional resistance of the lubricant is the unknown quantity.

The coefficient of friction is deduced from the data of observation in the following manner: Let

W = Weight on disks, lbs.
r_2 = Outer radius of fractional contact, feet.
r_1 = Inner " " " " "

r = Radius of any infinitesimal ring or band of the frictional surface, feet.
N = Number of revolutions per minute.
F = Reading on dynamometer, lbs.
L = Length of lever arm of upper disk, feet.
f = Coefficient of friction.

Suppose that the annular surfaces of the disk be divided into an infinite number of elementary areas by equidistant circles and radial lines, then will

Width of elementary band $= dr$. . . . . (1)

Angle between two successive radial lines $= d\theta$. . . . . (2)

Length of arc between two radii $= rd\theta$. . . . . . . (3)

Elementary area $= rdrd\theta$. . . . . . (4)

Area of annulus $= \pi(r^2 - r_1^2)$. . . . . (5)

Pressure per unit of area $= \dfrac{W}{\pi(r_2^2 - r_1^2)}$. . . . . (6)

Pressure on elementary area $= \dfrac{Wrdrd\theta}{\pi(r_2^2 - {}_1^2)}$. . . . . (7)

Friction on elementary area $= \dfrac{fWrdrd\theta}{\pi(r_2^2 - r_1^2)}$. . . . . (8)

Moment of friction on elementary area

$$= \frac{fWr^2drd\theta}{\pi(r_2^2 - r_1^2)}. \quad . \quad . \quad . \quad . \qquad (9)$$

Moment of friction on entire disk $= \dfrac{fW}{\pi(r_2^2-r_1^2)}\displaystyle\int_{r_1}^{r_2}\int_0^{2\pi} r^2drd\theta$. (10)

Integrating $= \dfrac{2\pi fW}{\pi(r_2^2 - r_1^2)}\left\{\dfrac{r^3}{3}\right\}_{r_1}^{r_2}$. . . (11)

Substituting the limits $= \dfrac{2fW(r_2^3 - r_1^3)}{3(r_2^2 - r_1^2)}$. . . . (12)

Work of friction per minute $= \dfrac{4f\pi WN(r_2^3 - r_1^3)}{3(r_2^2 - r_1^2)}$. . (13)

The work of the dynamometer $= 2\pi LFN$. . . . . . (14)

The friction equals the resistance; hence

$$\frac{4f\pi WN(r_2^3 - r_1^3)}{3(r_2^2 - r_1^2)} = 2\pi LFN; \quad \ldots \quad (15)$$

$$f = \frac{3FL(r_2^2 - r_1^2)}{2W(r_2^3 - r_1^3)};$$

$$= aF \div W; \quad \ldots\ldots \quad (16)$$

in which the constant coefficient may be easily determined by each machine.

The work done by this machine will be referred to at some length in the succeeding chapter.

In the construction of the Riehlé machine, which is shown in Fig. 39, the inventors have introduced a "balanced" weighing arrangement, and the combination, first used by the Author, of a device for indicating the coefficient of friction with those for determining pressure and velocity of rubbing.

The counter-pulleys admit of running the journals at different speeds, and any pressure can be applied up to 2200 lbs. (1000 kgs.). The thermometer and counter indicate the heat of the journal during the different stages of the testing, and the number of revolutions made by the journal. The coefficient of friction can be accurately determined by observing the pressure and friction as indicated by the beam, in connection with size of journal. The beams are graduated like scale-beams, and balanced. One weighs the pressure produced by the wheel and screw on the journals, one is used as a counterbalance, while the third measures the friction produced when the machine is in motion.

130. Thurston's Lubricant-Testing Machine.—The machine devised by the Author was, so far as he is aware, the first in which it was made possible to obtain from indices on the machine measures of the velocity of rubbing and speed of revolution, the total pressure and the intensity of pressure on the journal, the temperature and the friction, and easily to determine the exact value of the coefficient of friction. The Author, some time previous to the year 1872, found that the de-

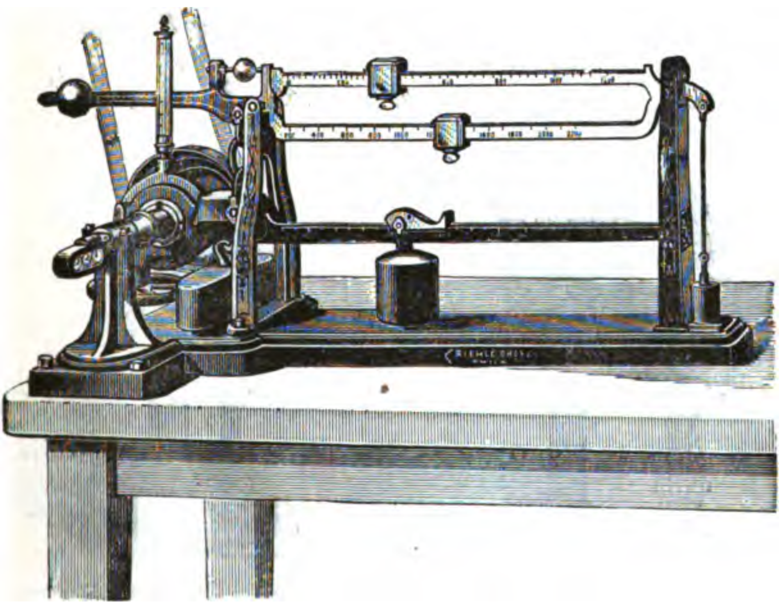

FIG. 39.—THE RIEHLÉ MACHINE.

termination of the amount of frictional resistance had been seldom attempted, but that the simple measurement of the heating by means of machines of the Ingham & Stapfer class had been relied upon alone, and that results obtained were of value only by comparison. He therefore endeavored to devise a machine which should not only exhibit the heating of a lubricated journal, under pressures and speeds variable at will, but one that should also give at the same time and with accuracy the more delicate but much more important measure of the friction. It was desirable that the machine should give not only a

measure of the resistance due to friction, but an exact measure of the relation which that resistance bears to the total load on the journal; in other words, it should give, directly and precisely, the value of the "coefficient of friction."

The construction of this machine is shown in Figs. 40 and 41, below.

At *F* is the journal on which the lubricating material is to be placed for test. This journal is carried on the overhung extremity of shaft *A*, which is sustained by the journals *BB'*, on a standard, *D*, mounted on a base-plate, *E*. The shaft

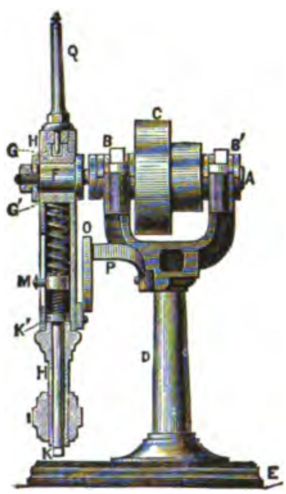

FIG. 40.—THURSTON'S MACHINE.

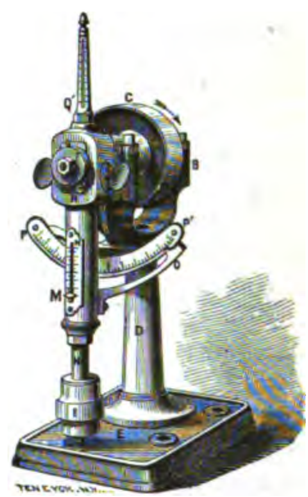

FIG. 41—THURSTON'S MACHINE.

is driven by a pulley, *C*, at any desired speed. A counter is placed at the rear end of this shaft, to indicate the number of revolutions. The shaft is usually driven at a fixed speed, corresponding to a velocity of rubbing surfaces approximating that of the journals on which it is proposed to use the oil. The testing-journal, *F*, is grasped by bearings of bronze, *GG'*, and with a pressure which is adjusted by the compression of a helical spring, *J*. This spring is carefully set, and the total pressure on the journal and the pressure per square inch are both shown on the index-plate, *N*, by a pointer, *M*. Above

the journal is a thermometer, *Q*, of which the bulb enters a cavity in the top " brass," and which indicates the rise in temperature as the test progresses.

The "brasses," thermometer, and spring are carried in a pendulum, *H*, to which the ball, *I*, is fitted; and the weights are nicely adjusted, and, as nearly as may be, in such a manner that the maximum friction of a dry but smooth bearing shall just swing it out into the horizontal line. The stem, *KK'*, of the screw, which compresses the spring, projects from the lower end of the pendulum, and can be turned by a wrench. A pointer, *O*, traverses an arc, *PP'*, and indicates the angle assumed by the pendulum at any moment. This angle is large, with great friction, and very small with good lubricating materials. This arc is carefully laid off in such divisions that, dividing the reading by the pressure shown on the index, *N*, gives the corresponding coefficient of friction.

The figures on the arc are the measure of the actual resistance of friction on the surface of the journal. Dividing this frictional resistance by the total load gives the value of the coefficient. As there is no intermediate mechanism, this measure is obtained without possible error; and, as the resisting moment changes very rapidly at low angles, great precision of measurement is obtained, as will be seen when the results of experiment are given. The machine can also be arranged to give readings of this coefficient directly.

The theory of the machine is as follows: Let

$R =$ radius to centre of gravity of pendulum;
$F =$ effort due to weight of arm;
$r =$ radius of journal;
$l =$ length of journal;
$W =$ weight of pendulum complete;
$P =$ total pressure on journal;
$p =$ pressure per square inch of longitudinal section;
$T =$ tension on spring;
$\theta =$ angle between arm and a perpendicular through axis;
$f =$ coefficient of friction;
$Q =$ total friction.

When Θ is equal to 90°,

$$FR = Qr. \quad \ldots \ldots \quad (1)$$

And when any other angle,

$$FR \sin \theta = Qr. \quad \ldots \ldots \quad (2)$$

Solving equation (2) with respect to Q,

$$Q = \frac{FR \sin \theta}{r}. \quad \ldots \ldots \quad (3)$$

The coefficient of friction is

$$f = \frac{Q}{p} = \frac{FR \sin \theta}{rP}. \quad \ldots \ldots \quad (4)$$

The pressure per square inch is

$$p = \frac{P}{4lr} = \frac{2T + W}{4lr}. \quad \ldots \ldots \quad (5)$$

From this last equation the graduations on the right-hand side of the index-plate are deduced.

From the equation

$$N = 4plr \quad \ldots \ldots \quad (6)$$

the numbers on the left-hand side are determined.

By substituting in equation (1) the value of Q, in terms of the coefficient and total pressure, from (4) it becomes

$$FR = f(4plr)r \quad \ldots \ldots \quad (7)$$

Solving with respect to f, equation (7) becomes

$$f = \frac{\frac{FR}{r}}{4plr} \quad \ldots \ldots \quad (8)$$

From the numerator of the second number of equation (8) the graduations on the arc are deduced.

In applying the foregoing equations to the machine shown

in the engraving, the following numerical values may be given to the respective symbols:

$F = 2.5$ lbs.; $R = 10$ in.; $r = .625$ in.; $l = 1.5$ in.; $4lr = 3.75$ sq. in.; $w = 6$ lbs. Also, a compression of $1\frac{3}{8}$ inches of the spring corresponds to a tension of 100 lbs.; hence, for each pound's tension the spring will be compressed .01375 of an inch.

The graduations on the right-hand side of the scale are obtained from equation (5):

$$p = \frac{2T + W}{4lr}. \quad . \quad . \quad . \quad . \quad . \quad . \quad (4)$$

The first graduation will naturally be that value of p when T is equal to 0, which value is 1.6.

The speed of the machine, when the belt is upon the largest pulley of the cone, C, should be that which will give at the surface of the testing-journal the least speed of rubbing, which is expected usually to be adopted.

The figures on the arc PP', traversed by the pointer O, attached to the pendulum, are such that the quotient of the reading on the arc PP', by the total pressure read from the front of the pendulum at MN, gives the "coefficient of friction," i.e., the proportion of that pressure which measures the resistance due to friction.

A printed table furnished with each machine gives these coefficients for a wide range of pressures and arc-readings.

To determine lubricating quality, remove the pendulum HH from the testing-journal GG', adjust the machine to run at the desired pressure, by turning the screw-head K projecting from the lower end of the pendulum, until the index M above shows the right pressure, and adjust it to run at the required speed by placing the belt on the right pulley, C.

Next throw out the bearings, by means of the two little cams on the head of the pendulum, H, in the small machine, or by setting down the brass nut immediately under the head in the large machine; then carefully slide the pendulum upon the testing-journal, GG', and at the same time see that no scratching of journal or brasses takes place,

Oil the journal through the oil-cups or the oil-holes, set the

machine in motion, running it a moment until the oil is well distributed over the journal. Next stop the machine; loosen the nut or the cams which confine the spring, and, when it is fairly in contact and bearing on the lower brass with full pressure, turn the cams or the brass nut fairly out of contact, so that the spring may not be jammed by their shaking back while working. Start the machine again and run until the behavior of the oil is determined, keeping up a free feed throughout the experiment.

At intervals of one or more minutes, as may prove most satisfactory, observations and records are made of the temperature given by the thermometer, *Q*, and the reading indicated on the arc *P*, of the machine, by the pointer *O*. When both readings have ceased to vary, the experiment may be terminated.

The pendulum is then removed, the pressure of the spring being first relieved, and the journal and brasses are cleaned with exceedingly great care; care is taken to have no particle of lint on either surface, or any grease in the oil-cups or oil-passages.

The journal may be cleansed, after each test, either with alcohol, gasoline, or benzine. The effect of an oil is often felt in successive tests, long after starting with a new lubricant.

A comparison of the results thus obtained with several oils will show their relative values as reducers of friction.

Steam-cylinder lubricants are tested upon bearings heated to a temperature corresponding to any desired steam-pressure. When the maximum temperature has been attained the flame is removed, and the behavior of the oil noted as the temperature falls to 212° F., which corresponds to atmospheric pressure or to zero on the steam-gauge. Any effervescence or excessive friction at the higher temperatures condemns the lubricant. It is the custom to take the average of the coefficients of friction for temperatures ranging from 340° F.—corresponding to a gauge-pressure of 104 lbs.—to 212° F.

In each case the results are recorded in tables on the blanks (of which a copy is given on the next page) which are sent with the machine, and which exhibit—

RECORD OF TESTS OF LUBRICANTS.

Laboratory No............ *Original Mark*................ *Source*.....................

Composition..
....
....
Investigation..
....
....

Coefficient of Friction = $\frac{\text{Friction in Pounds}}{\text{Total Pressure.}}$

No. of Test..............................	......	......	......
Pressure on Journal, lbs. per square inch	......	......	......
Total Pressure on Journal, lbs	......	......	......
Amount of Oil used on Journal, m. g..............	......	......	......
Average Coefficient of Friction...............	......	......	......
Minimum " " "	......	......	......
Total Number of Revolutions	......	......	......
Total Number of Feet travelled by rubbing surface......	......	......	......
Elevation of Temperature, max...............	......	......	......

Time, minutes.	Revolutions.	Temperature.	Friction, pounds.	Coefficient of Friction.	Time, minutes.	Revolutions.	Temperature.	Friction, pounds.	Coefficient of Friction.	Time, minutes.	Revolutions.	Temperature.	Friction, pounds.	Coefficient of Friction.

(1) The pressure and speed of rubbing at each trial. (2) The observed temperatures. (3) The readings on the arc of the machine. (4) The calculated coefficients of friction.

At the end of the trial the average and the minimum coefficients are entered, and the total distance *rubbed over* by the bearing surfaces.

To determine the liability of the oil to gum, the bearings are lubricated with a definite quantity of the oil, and the machine run a certain number of revolutions. The temperature of the bearings and the friction at the end of this period are noted. Both journal and brasses are then removed, placed under a glass receiver, which excludes the dust yet permits the entrance of air, and are left there for any desired length of time, as for one day. At the end of that time the bearings are replaced in the machine, and the latter is driven until the temperature of the bearings is the same as at the previous trial; the friction is then again noted. Any increase of friction above that previously observed must be due to the gumming of the lubricant. For the machine described, the standard quantity of the lubricant is 16 milligrammes, which is ample to afford perfect lubrication of the bearing surfaces during the trials. The number of revolutions at the first trial is often 5000; it may, however, vary considerably without affecting the results, so long as it is too small to affect the wearing qualities of the lubricant, as within this limit the friction remains constant with a constant temperature. Changes in temperature and friction always accompany each other; it is for this reason that great care is taken to obtain the same temperature of bearing at each trial.

To determine durability, proceed as in determining the friction, except that the lubricant should not be continuously supplied, but should be fed to the bearing a small and definite portion of time—as a drop or two for each two inches length of journal. Extreme care should be taken that each portion actually reaches the journal and is not lost, either in the oil-hole or by being wiped off the journal, and that the portions applied are *exactly* equal. When the friction, as shown by the pointer O, has passed a minimum and begins to rise, the ma-

chine should be carefully watched, and should be stopped, either at the *instant* that the friction has reached double the minimum, or when the thermometer indicates 212° F.; or another portion of the lubricant should be then applied to the journal.

This operation should be repeated until the duration of each trial becomes nearly the same; an average may then be taken either of the time, of the number of revolutions, or of the distance rubbed over by the bearing, which average will measure the durability of that lubricant. Next carefully clean the testing-journal, and proceed as before with the next oil to be tested.

In making comparisons, always test the standard, as well as the competing oils, on the same journal and under *precisely* the same conditions.

It was formerly the custom to continue the trial until the temperature of the bearing, as indicated by the thermometer, attained a certain point, as 120° or 200° F., and to take the number of revolutions of the journal or the number of feet traversed, up to that point, as a measure of endurance. The real endurance, however, of the lubricating material bears no definite proportion to the range of temperature thus observed.

Another method is adopted by the boards of U. S. naval engineers sometimes appointed to test oils at the navy-yards. The quantity of oil required to keep down the temperature of journal to a certain figure, as 110° or 115° F. (44° to 46° C.), during a definite period, as one hour, five hours, or twenty-four hours, is measured, and the endurance is taken as inversely proportional to these amounts.

The Author considers the endurance of a lubricant to be measured by the length of time that it will continue to cover and lubricate the journal and prevent abrasion. When an oil is placed upon a journal, and there subjected to wear without renewal, it gradually assumes a pasty or gummy condition, slowly losing its lubricating power, and finally either increases friction to an objectionable extent, or oftener becomes so far expended as to permit the two rubbing surfaces to come into contact. It has been the custom of the author to run until

this occurs, and then to take the length of the run as a measure of the endurance of the oil.

It is extremely difficult to obtain successive measures of similar value even by this method; but by taking an average of several successive trials—or many, if necessary—the true measure of the endurance of lubricants can be obtained with any desired or necessary accuracy. This method involves more risk of injury to the journal than the other, and sometimes considerable loss of time in bringing the rubbing surfaces back into good condition again before going on to make other tests. The determination of the real value of the lubricant is usually of sufficient importance, however, to justify whatever time, trouble, and expense may be thus incurred.

This machine did such good work as to encourage the Author to design one especially fitted for railroad work.

The journal of this machine is of standard size, $3\frac{1}{4}$ inches diameter and 7 inches long. The speed is intended to be adjusted to velocities varying from that of a twenty-six-inch engine-truck wheel at sixty miles an hour down to that of a forty-two-inch wheel running fifteen miles an hour. The pressures are adjustable from a minimum total pressure up to 400 lbs. per square inch (28 kgs. per sq. cm.), or a load of nearly 10,000 lbs. (4545 kgs.) on the journal.

Fig. 42 is a side elevation of the larger machine, with the journal and pendulum in section, and Fig. 43 a front elevation. It consists of a shaft, *AB*, which is driven by a cone-pulley, *C*, the whole mounted on a cast-iron stand, *D*, terminating in a forked end at the top, with two bearings, *E* and *F*, in which the shaft runs. The shaft projects beyond the journal *F*, and the projecting part *A* is provided with a sleeve or bushing, *mm*, the outside of which forms a journal on which the tests of oil are made. A pendulum, *AG*, is suspended from this journal with suitable bearings, *aa*, which work on the journal *mm*; the heavy weight, *G*, attached to the lower end, is now omitted. It is evident that the friction on the journal *mm* will have a tendency to move the pendulum in the direction of the revolution of the shaft, and that the greater the friction on the journal the farther will the pendulum swing. A scale or

dial, *HI*, is attached to the stand, and the distance the pendulum swings may be read off on this scale, which thus indicates the coefficient of friction of the lubricant on the journal. In order to get any desired pressure of the bearings on the journal, the pendulum is constructed as follows: A wrought-iron pipe, *J*, which is represented in Fig. 42 by solid black shading,

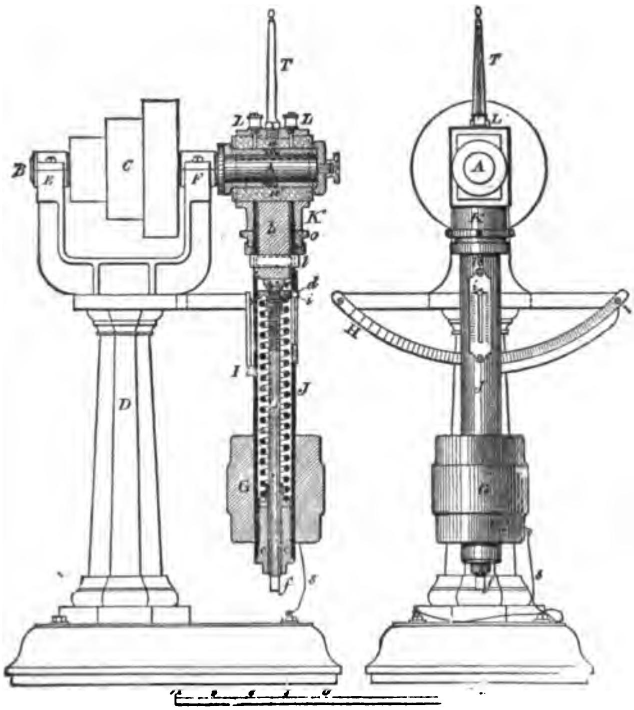

FIG. 42. FIG. 43.

THURSTON'S "RAILROAD MACHINE."

is screwed into the head *K*, which embraces the journal and holds the bearings ***aa*** in their place. In this pipe a loose piece, ***b***, is fitted which bears against the under journal-bearing ***a'***. Into the lower end of the pipe a piece, *cc*, is screwed with a hole drilled in the centre through which a rod, *J*, passes, the upper end of which is screwed into a cap, ***d***; between this cap

and the lower piece, *cc*, a spiral spring shown in section in Fig. 42 is placed.

The upper end of the rod has a cap, *e*, in which it turns and which bears against the piece *b*, which in turn bears against the bearing *a'*. If the rod is turned with a wrench applied to the square head at *f*, it is obvious that the cap *d* will be either drawn down on the spiral spring, which will thus be compressed, or it will be moved upward, and the spring will thus be released, according to the direction in which the rod is turned. If the spring is compressed, its lower end will bear against the under cap and on the piece *cc*, by which the pressure will be transmitted to the pipe *J*, and thence to the head *K*, and from that on the upper journal-bearing *a*; while at the same time the upper end of the spring bears against the cap *d*, which, being screwed on the rod *f*, transmits its pressure upward to the cap *e*, and from that to the loose piece *b*, and from that to the upper journal-bearing *a*. It will thus be seen that any desired pressure within the limits of the elasticity of the spiral spring may be brought upon the journal and bearings by turning the rod *f*. The piece *b* has a key, *l*, which passes through it and the pipe *J*. This key bears against a nut, *o*, which is screwed on the pipe, its object being to provide a ready means of relieving the journal of pressure by simply turning the nut *o* when it is desired to do so. An index, *i*, is attached to the spiral spring so as to show the position of the latter.

A counterbalance is sometimes used to reduce the "moment" of the pendulum, when very fine readings are desired. This modification necessitates a corresponding change of the scale on the arc of the machine. (See Frontispiece.)

The "brasses" are cast hollow, and when desired a stream of water is driven through them to keep the rubbing surfaces cool and at uniform temperature. This plan was adopted many years ago by Hirn, to secure uniformity and manageability of temperatures. This provision insures great exactness of determinations. Provision for lubrication by the oil-bath is sometimes advisable for special work.

The oil is fed to the journal by means of oil-cups, *LL*, on the top of the head *K*, and a thermometer, *T*, is attached be-

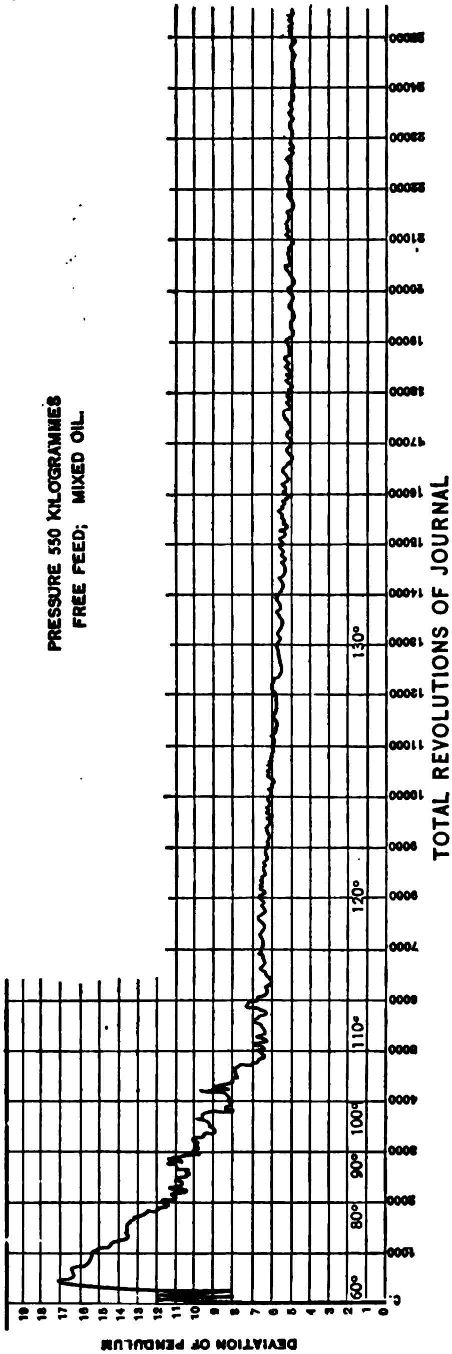

FIG. 44.—AUTOGRAPHIC RECORD OF OIL-TEST.

tween the two cups, and from it the rise in temperature is observed. A cord, *s*, is attached to the pendulum in some cases, to prevent its being thrown beyond the intended limit.

The Pratt & Whitney Co., of Hartford, U. S., and Messrs. W. H. Bailey & Co., of Salford, G. B., the builders of these machines, have slightly modified some of their details, but have retained all essential features as in the frontispiece.

131. **Lux's Improvement** on Thurston's machine consists in the addition of an automatic recording apparatus. The pendulum of the machine carries an arm, which raises and depresses a slide at the right, which slide carries a pencil. A cylinder is mounted behind the pencil-slide, and is connected with clockwork, by which it is made to revolve uniformly at any convenient rate. Paper wound on this cylinder is thus made to move under the pencil at a constant rate, and the rise and fall of the latter is proportional to the swing of the pendulum, and varies with the friction at the journal. The paper is suitably lined, in such manner that the diagram so made can be conveniently read, the abscissas of the curve measuring the times and the vertical scale giving the friction. The pressure is adjusted and the temperature readings taken as before.

The preceding figure exhibits the form of diagram obtained during tests of oils in the manner just described.

132. **Illustration of Method, Record, and Report.**—*Results of Trials of an Oil marked X, and its comparison with Standard Bleached Winter Sperm and Pure Lard Oils.*

In illustration of the method frequently adopted by the Author in making a tolerably complete investigation, we have the following:

These oils were tested on a "lubricant-testing machine" of the "77" style, by the method already described. The standard bleached winter sperm and a pure lard oil were tested with the X oil on the same bearing and under precisely similar conditions. The following are records of data obtained during these tests:

RECORD OF TESTS OF LUBRICANTS.—WINTER-BLEACHED SPERM AND LARD OILS.

Laboratory Nos. 90 and 93; Original Marks, Standard Sperm, Penn. Lard; Sources, New Bedford and P. R. R.

Investigation—To determine the Power of reducing Friction; Coefficient of Friction= $\frac{\text{Reading on Arc}}{\text{Total Pressure}} = \frac{\text{Pressure}}{\text{Friction.}}$

No. of Test, 1, 2 Sperm, 1, 2, Lard; Pressure on Journal, lbs. per square inch, 50, 100 Sperm, 50, 100 Lard. Total pressure on Journal, lbs., 200, 400 Sperm, 200, 400 Lard; Amount of oil used on Journal, continuous supply; Average Coefficient of Friction, .0050, .0037 Sperm, .0100, .0062 Lard; Total number of feet travelled by rubbing surface, per minute, 237.3, 235.1 Sperm, 233.8, 229.2 Lard; Elevation of temperature, max., 8, 10 Sperm, 9, 12 Lard.

Time, minutes.	Revolutions.	Temperature.	Reading on Arc.	Coefficient of Friction.	Time, minutes.	Revolutions.	Temperature.	Reading on Arc.	Coefficient of Friction.	Time, minutes.	Revolutions.	Temperature.	Reading on Arc.	Coefficient of Friction.
							Sperm Oil No. 1.							
At start.		90	1.5		20		96	1		40		98	1	
5		93	1		25		97	1		45		98	1	
10		94	1		30		98	1		55		98	1	
15		95	1		35		98	1		60		98	1	
							Test No. 2.							
At start.		90	2		20		98	1.5		40		100	1.5	
5		93	1.5		25		100	1.5		45		100	1.5	
10		95	1.5		30		100	1.5		50		100	1.5	
15		97	1.5		35		100	1.5		60		100	1.5	
							Lard Oil No. 1.							
At start.		90	2		20		98	1.5		40		99	1.5	
5		93	1.5		25		99	1.5		45		99	1.5	
10		95	1.5		30		99	1.5		50		99	1.5	
15		96	1.5		35		99	1.5		60		99	1.5	
							Test No. 2.							
At start.		90	3		20		98	2.5		40		102	2.5	
5		93	2.5		25		100	2.5		45		102	2.5	
10		95	2.5		30		102	2.5		50		102	2.5	
15		97	2.5		35		102	2.5		60		102	2.5	

RECORD OF TESTS OF LUBRICANTS.—WINTER-BLEACHED SPERM AND LARD OILS.

Laboratory Nos. 90 and 93; Original Marks, Pure Sperm, Penn. Lard; Source, New Bedford and P. R. R.

Investigation—To determine the Durability of the Oils; Coefficient of Friction = $\frac{\text{Reading on Arc}}{\text{Total Pressure.}} = \frac{\text{Friction}}{\text{Pressure.}}$

No. of Test, 1 Sperm, 1 Lard; Pressure on Journal, lbs. per square inch, 75 Sperm, 75 Lard; Total pressure on Journal, lbs., 300 Sperm, 300 Lard; Amount of oil used on Journal, m. g., 8 Sperm, 8 Lard; Average Coefficient of Friction, — Sperm, — Lard; Minimum Coefficient of Friction, — Sperm, — Lard; Total number of revolutions, 27,870 Sperm, 24,500 Lard; Total number of feet travelled by rubbing surface, 97,266 Sperm, 85,505 Lard; Elevation of temperature, max., 35 Sperm, 55 Lard.

Time, minutes.	Revolutions.	Temperature.	Reading on Arc.	Coefficient of Friction.	Time, minutes.	Revolutions.	Temperature.	Reading on Arc.	Coefficient of Friction.	Time, minutes.	Revolutions.	Temperature.	Reading on Arc.	Coefficient of Friction.
SPERM OIL.														
At start.		65	3		60		100	4.5		77	26,560	100	6	
1		65	4		62		100	5			Redistributed oil.			
5		70	4		63	23,010	100	6		79		100	4.5	
10		78	4			Redistributed oil.				80		100	5	
15		85	4		65		100	3		82	27,590	100	6	
20		93	4		68		100	5			Redistributed oil.			
25		95	4		70	24,860	100	6		84		100	5.5	
30		98	4			Redistributed oil.				85	27,870	100	6	
40		100	4		72		100	3			Redistributed oil.			
50		100	4		75		100	5.5		87		100	6	
LARD OIL.														
At start.		65	5		45		118	9		64		120	8	
1		65	6		50	17,810	120	10		65		120	9	
5		75	6			Redistributed oil.				66	22,500	120	10	
10		85	6		52		120	5			Redistributed oil.			
15		95	7		53		120	6		68		120	7	
20		100	8		55		120	7		69		120	8	
25		105	9		57		120	8		70		120	8.5	
30	11,120	110	10		58		120	8.5		72		120	9	
	Redistributed oil.				59		120	9		73	24,190	120	10	
32		110	5		60	20,660	120	10			Redistributed oil.			
35		110	6.5			Redistributed oil.				75		120	8	
38		113	7		61		120	5.5		76	24,500	120	10	
40		115	8		62		120	6.5			Redistributed oil.			
43		118	9		63		120	7.5		78		120	10	

RECORD OF TESTS OF LUBRICANTS.—OIL MARKED X.

Original Mark. X.

Investigation—To determine the Durability of the Oil; coefficient of Friction $= \frac{\text{Reading on Arc}}{\text{Total Pressure}} = \frac{\text{Friction}}{\text{Pressure.}}$

No. of Test, 1, 2; Pressure on Journal, lbs. per square inch, 75, 75; Total pressure on Journal, lbs., 300, 300; Amount of oil used on Journal, m. g., 8, 8; Total number of revolutions, 25,720, 27,040; Total number of feet travelled by rubbing surface, 8976, 10,136.9; Elevation of temperature, max., 95, 115.

Time, minutes.	Revolutions.	Temperature.	Reading on Arc.	Coefficient of Friction.
At start.		65	11	
5		85	10	
6		88	8	
10		95	8	
15		110	10	
20		120	11	
24	7,500	120	16	
Redistributed oil.				
27		120	8	
30		120	8	
35		120	9	
40		123	10	
42	11,920	125	16	
Redistributed oil.				

Time, minutes.	Revolutions.	Temperature.	Reading on Arc.	Coefficient of Friction.
45		125	9	
48		125	10	
50		128	11	
53		128	12	
55		130	12	
60		135	12	
65		140	15	
66	17,940	140	16	
Redistributed oil.				
67		140	11	
68		140	12	
69		143	13	
70		145	14	
71		145	15	

Time, minutes.	Revolutions.	Temperature.	Reading on Arc.	Coefficient of Friction.
72	19,280	145	16	
Redistributed oil.				
73		145	13	
74		148	14	
75		150	14	
80		150	14	
85		155	14	
90		160	14	
92		160	15	
93	25,720	160	16	
Redistributed oil.				
94		160	16	

TEST No. 2.

Time, minutes.	Revolutions.	Temperature.	Reading on Arc.	Coefficient of Friction.
At start.		65	10.5	
5		90	11.5	
10		115	11.5	
15		130	11	
20		140	10.5	
40		150	10.5	
45		150	12	
46		150	13	

Time, minutes.	Revolutions.	Temperature.	Reading on Arc.	Coefficient of Friction.
47		153	15	
48	17,800	155	20	
Redistributed oil.				
49		155	10	
50		155	13	
51		158	14	
52		158	15	
55		160	13.5	

Time, minutes.	Revolutions.	Temperature.	Reading on Arc.	Coefficient of Friction.
60		165	13.5	
65		170	14	
70		175	14.5	
75	27,040	180	20	
Redistributed oil.				
77		180	20	

[The redistribution occasionally effected to secure complete utilization was done with the tip of the finger of the observer.]

RECORD OF TESTS OF LUBRICANTS.—OIL MARKED X.

Original Mark, X. Composition—An unknown mixture of mineral and perhaps other oils with powdered graphite.
NOTE.—Graphite separated when left undisturbed in my study.*

Investigation—To determine Power of reducing Friction; Coefficient of Friction = $\frac{\text{Reading on Arc}}{\text{Total Pressure}} = \frac{\text{Friction}}{\text{Pressure.}}$

No. of Test, 1, 2; Pressure on Journal, lbs. per square inch, 50, 100; Total pressure on Journal, lbs., 200, 400; Amount of oil used on Journal, continuous supply; Average Coefficient of Friction, 0.206, 0.168; Minimum, .0200, .0125; Total number of feet travelled by rubbing surface, per minute, 23,517 2305; Elevation of temperature, max., 10, 40.

Time, minutes.	Revolutions.	Temperature.	Reading on Arc.	Coefficient of Friction.	Time, minutes.	Revolutions.	Temperature.	Reading on Arc.	Coefficient of Friction.	Time, minutes.	Revolutions.	Temperature.	Reading on Arc.	Coefficient of Friction.
At start.		90	5		20		98	4		45		100	4	
1		91	5		25		98	4		50		100	4	
5		95	5		30		98	4		55		100	4	
10		98	4.5		35		98	4		60		100	4	
15		98	4		40		98	4						

TEST No. 2.

Time, minutes.	Revolutions.	Temperature.	Reading on Arc.	Coefficient of Friction.	Time, minutes.	Revolutions.	Temperature.	Reading on Arc.	Coefficient of Friction.	Time, minutes.	Revolutions.	Temperature.	Reading on Arc.	Coefficient of Friction.
At start.		90	15		20		128	5		45		105	5	
1		100	17		25		120	6		50		105	5	
5		130	20		30		110	5		55		105	5	
10		128	8		35		105	5		60		105	5	
19		128	10		40		105	5						

* Good plumbago-oils should not give a precipitate, however long left undisturbed.

From the preceding logs of tests were deduced the following results and conclusions:

AVERAGE COEFFICIENTS OF FRICTION.

Lab. No.	Name of Oil.	Pressure per Square Inch. 100	50	Average.
90	W. B. Sperm	0.0037	0.0050	0.00435
	X	0.0168	0.0206	0.0187
93	Lard	0.0062	0.0100	0.0081

The relative values of these oils in reducing friction, taking sperm-oil as a standard, and giving it a value of 100, will be represented by the quotients obtained by dividing the coefficients for sperm by those for each of the other oils, and multiplying by 100.

The following table gives these quotients:

RELATIVE POWER OF REDUCING FRICTION.

Name of Oil.	Pressure per Square Inch. 100	50	Average.
W. B. Sperm	100.0	100.0	100.0
X	22.0	24.2	23.2
Lard	59 6	50.0	53.7

The speed was about 700 revolutions per minute (244.3 ft., 74 m.), giving a speed of rubbing surface corresponding to about 35 miles per hour for a 33-inch (79 cm.) wheel in railroad service. Dividing the coefficients for the oils by the coefficient for sperm and multiplying by 100, we obtain the following tabulated figures as the relative amount of power consumed in using the respective oils.

A common standard pressure and speed for such tests is, on some roads, 250 lbs. per square inch, and a speed equivalent to 15 miles per hour for the axle-journal, at a temperature of 100° F.

RELATIVE POWER CONSUMED.

Name of Oil.	Pressure per Square Inch.		
	100	50	Average.
W. B. Sperm	100.0	100.0	100.0
X	481.0	412.0	429.8
Lard	167.6	200.0	186.2

As regards friction, sperm excels, lard stands next, and X next.

From the results of the tests of durability, we find the following:

DURABILITY, OR WEARING POWER.

	Revolutions.	Ft. travelled.
W. B. Sperm	27,870	9.726.6
X (average)	26,380	9.206.6
Lard	24,500	8.550.5

Taking bleached winter-sperm oil as a standard, and assuming its value to be 100, the values of the oils as regards durability will be represented by 100 times the quotient obtained by dividing the number of revolutions or feet travelled of each oil by the feet run by sperm. We thus obtain the following:

RELATIVE DURABILITY.

W. B. Sperm	100.0
X	94.6
Lard	87.9

The figures in this last table are measures of the lengths of time that equal quantities of each oil would run, so that the greater the figures of this table the more valuable the oil.

The value of an oil may be taken as greater in proportion as the figures in the above table are greater, and as the figures in the table headed "Relative Power of Reducing Friction" are greater, so that combining the results given in both tables, the relative values of the oils, sperm-oil being the standard and taken at 100, may be represented by one one-hundredth the product obtained by multiplying the figures in the last column of the table headed "Relative Durability" by those in the last column of the table headed "Relative Power of Reducing Friction." The following are therefore the relative values.

RELATIVE VALUES OF THE OILS.

W. B. Sperm	100.0
X	21.9
Lard	47.2

SECOND TEST.

A second test consisted in cutting a square hole in the lower box and packing it with waste saturated with the oil to be tested. The oil to be tested was spread on the journal and a pressure of 100 lbs. per square inch (43 kgs. per sq. cm.) was applied; the machine was then started and allowed to run until the friction had increased to double the least amount shown at any time during the test. Both the X and the lard oils were tested by this method. In each case 743 milligrammes weight of waste was used as packing. The waste was in each case thoroughly saturated with the oil and weighed before and after the test. In the case of X, the waste absorbed 4.806 grms. and contained 2.229 grms. at the end of the test, so that the oil consumed was 2.577 grms. In the case of the lard, 4 grms. were also absorbed by the waste; 7.265 grms. remained; so that the useful consumption was 2.735 grms. X ran 266,226 ft. = 54.2 miles per gramme consumed, with an average coefficient of friction of 0.0318, and lard-oil ran 182,528.7 ft. = 34.5 miles per gramme consumed, with an average coefficient of friction of 0.0244, the former excelling the latter about *sixty per cent.*

THIRD TEST.

A third test was made upon the "R. R. Standard Machine," and the following are the coefficients of friction obtained:

AVERAGE COEFFICIENTS OF FRICTION.

OIL.	Pressure per Square Inch and Total.		
	150, 2629	300, 5250	Average.
W. B. Sperm	0.008	0.0046	0.0063
X	0.024	0.015	0.0195
Lard	0.009	0.0059	0.0075

CHAPTER VII.

FRICTION OF LUBRICATED SURFACES—LAWS AND MODIFYING CONDITIONS.

133. **Variations of Friction of Lubricated Surfaces** occur, as has been already stated, with every change of physical condition of either the bearing and journal surfaces, or of the lubricant applied to them.* A rough pair of surfaces exhibits great resistance to relative motion, while this friction is constantly reduced as they become smoother with wear; but under some conditions the smoothness and the nicety of fit may be made too perfect, and the friction then increases again. An oil which works well, and gives a comparatively low coefficient under low pressures, may prove an inferior lubricant under heavy loads, and the same unguent may be a good, a bad, or an indifferent lubricant according to the temperature or the speed of the rubbing surface to which it is applied. It is even sometimes found to be the fact that, with some lubricants, and especially with light mineral oils, the total frictional resistance may be reduced, while nevertheless the bearing may show increased wear, the increase of resistance due to the exceedingly slow wear being compensated by the decrease in fluid resistance.

The conditions which produce most serious differences in ordinary work are the nature of the unguent, the pressure, and the temperature. Velocity of rubbing determines a limit beyond which the intensity of pressure cannot be carried without danger of heating; but the effect of its variation upon the

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* Friction and Lubrication. New York, 1879.

coefficient of friction is usually less considerable than is that of either of the other conditions specified.

The lubricating value of oils is even affected by moisture. It affects mineral oils very little, the moisture slightly increasing their resistance in the bearing. They have little tendency to absorb moisture from the atmosphere. Fatty oils are somewhat hygroscopic, and are quite sensibly affected by a trace of moisture.

Exposure to air produces a tendency in organic lubricants to acidify or to become resinous, the non-drying oils exhibiting the one and the drying-oils the other method of change. The purer the oil, as a rule, the less is the liability to change. Hirn, experimenting on the oils named below, found that some were rather better lubricants at the period of incipient rancidity than when fresh. Cocoa-nut oil was 7 per cent. and rape seed 3 per cent. better, while with other oils less difference is observed.

Working the oils for a week together, using an oil-bath, Hirn finds sperm-oil to alter least of all, very slowly increasing in resistance; neat's-foot next, then olive and rape-seed; while cocoa-nut oil depreciates most rapidly, and at a rapidly accelerated rate.

The time required to exhibit an acid reaction was as below:

Oils.	Time, hours.	Oils.	Time, hours.
Sperm. first quality	36	Cocoa nut	4
" second quality	36–38	Poppy	5
Lard	24	Rape seed, refined	12
Neat's-foot	30	" crude	24
Olive, limpid	24–30		

Sperm-oil was found to be the best lubricant in all these experiments.

The method of supply should b' carefully looked to, and a very free "feed," with a system of collection and reapplication of the oil leaving the bearing, will be found to give by far the greatest economy of power and cost. Experiments made for the Institution of Mechanical Engineers, in which oiling by a pad as in railway work, by a siphon lubricator or oil-cup, and by a bath, which keeps the surfaces flooded with oil, gave the

COEFFICIENTS OF FRICTION.

[*Journal of Cast Iron; Bearing, Bronze; Velocity,* 750 *feet* (230 *m.*) *per minute; Temperature,* 70° *F.* (21° *C.*). *Intermittent feed through oil-hole.*]

Name.	Pressures: Lbs. per Square Inch and per Square Cm.							
	8 0.56		16 1.12		32 2.24		48 3.36	
	Avge.	Min.	Avge.	Min.	Avge.	Min.	Avge.	Min.
Group I.								
Natural Summer Sperm	.1720	.1330	.1627	.1083	.102	.0833	.1180	.1050
" Winter Sperm	.2505	.1500	.1410	.1000	.0958	.0875	.0813	.0750
Bleached " "	.1920	.1583	.1600	.1330	.1172	.0916	.09907	.0944
" Summer Whale	.1866	.1333	.1383	.09166	.1109	.0874	.0881	.0777
Natural " "	.1986	.1500	.1482	.0916	.1316	.1086	.0951	.0722
" Winter Whale	.3296	.1833	.1902	.1250	.0925	.0750	.1444	.1000
Bleached " "	.1979	.1333	.1916	.1333	.1086	.1000	.0993	.0705
Winter Lard Oil	.2386	.1666	.1575	.1166	.1405	.1000	.1005	.0750
Extra Neat's-foot Oil	2242	1500	1621	.1000	.1166	.0916	.1138	.1055
Tallow Oil	.1840	.1500	1460	.1000	.0935	.0750	.1166	.0844
Refined Seal Oil	.1585	.1333	.1378	.1083	.1130	.0716	0986	.0750
Bleached Winter Elephant Oil	.1928	.1333	.1650	.1083	.0862	.0791	.0766	.0611
Group II.								
Olive Oil	.1668	.1333	.1575	.1000	.1681	.1000	.0930	.0555
Cotton-seed Salad Oil	.2156	.1577	.1757	.1250	.1444	1083	.0996	.0694
Palm Oil	.2826	.1666	.2041	.1250	.1116	0584	.1013	.0666
Rape-seed Oil	.1817	.1333	.1567	.1250	.1187	.0833	1063	.0722
Elaine Oil	.2597	.2000	.1842	.1500	.1277	.0833	.1305	.1111
Linseed Oil *	.1598	.1333	.1215	.0833	.1347	0750	.0962	.0609
Pea-nut Oil	.1910	.1500	.1688	.1333	.10052	.0792	.0833	.0550
Refined Cotton-seed Oil	.2125	.1666	.1401	.1249	.1166	.1000	.1100	.0800
Rosin Oil	.2765	.2650	.2452	.1500	.1170	.0833	.1028	.0844
Cocoa-nut Oil	.1750	1333	.1066	.0916	.1062	.0791†	.0794	†.0611
Cold-Pressed Castor Oil	.2375	.1916	.1380	.1125	.1026	.0708	.0944	.0722
Group III.								
Labrador Cod Oil	.2475	.1500	.1488	.1250	.1016	.0666	.0805	.0661
Tanner's Cod Oil	.2776	.2166	.1666	.1500	.0970	0833	.0880	.0833
Menhaden Oil	.2530	.1660	.1238	.1000	.1000	.0917	.1220	.1000
Group IV.‡								
Mineral Sperm Oil	.1875	.1333	.1604	.1416	.0861	.0791	.0944	.0944
Deod. White Lubricating	.1537	.1500	.1583	.1500	.1277	.1125	1277	.1277
Bleached Deod. Lubricating	.1833	.1333	.2333	.1500	.1250	.1166	.1222	.1222
Unbleached Deod. Lubricating	.2550	.1500	.2067	.1500	.1275	.1250	.1555	.1444
Kerosene *	.2330	.2165	.1729	.1416	.1250	.1250	.1770	.1770
Crude Lubricating	.1272	.1100	.1453	.1000	.1777	.1500	.1500	.1500
Paraffine	.2607	.2000	.1777	.1333	.1343	.1125	.2222	.2222
Group I.			**Second Series of Tests.**					
Natural Winter Sperm	.2072	.1333	.1661	.1291	.1302	.0958	.1155	.0888
Bleached " "	.1755	.1166	.1678	.1291	.1083	.0958	.0811	.0750
Natural " Whale	.2369	.2166	.1250	.1000	.1000	.0750	.0777	.0666
Bleached " "	.1747	.1333	.1483	.1133	.1333	0833	.0986	.0666
Winter Lard	.1959	.1583	.1770	.1250	.1095	.0666	.0758	.0666
Extra Neat's-foot	.1746	.1500	1254	.1000	.1198	.0791	.1159	.1000
Group II.								
Olive Oil	.1839	.1333	.1175	.0916	.0902	.0750	.1344	.0611
Refined Rape-seed (Yellow)	.1716	.1666	.1435	.1166	.1000	.0833	.0822	.0555
Winter-pressed Cotton-seed (White)	.1259	.1166	.0981	.0833	.0983	.0666	.0861	.0750
Winter-pressed Cotton-seed (White)	.1557	.1333	.1006	.0833	.0895	.0750	.0758	.0722
Group III.								
Menhaden Oil	.1637	.1333	.1685	.1083	.0982	.0625	.0963	.0888

* Not a lubricant.
† Values somewhat uncertain.
‡ All mineral oils here described are of uncertain composition.

following figures, showing an enormous advantage in the use of the last method:

METHODS OF OILING (RAPE-SEED OIL).

Velocity of rubbing, 157 feet (46 m.) per minute.

	Actual Load.		Coefficient of Friction.	Comparative Friction.
	Kilogs. per sq. cm.	lbs. per sq. in.		
Oil Bath.............	18.5	263	0.00139	1
Siphon Lubricator....	17.7	252	0.00980	7.06
Pad under Journal....	19 1	272	0.00900	6.48

The lowest of these values of the coefficient are below any reached by the Author, or, up to their date, probably, ever recorded.

134. Commercial Oils, under moderate pressures, vary greatly in their power of reducing friction. The table of values (p. 276) obtained by the Author by experiment, using the testing-machine devised by him, exhibits the effect of variation of pressure in changing these values, as well as the differences in oils, all of which were supposed to be pure. These values may probably be assumed as correct, and applicable in the ordinary work of the designing engineer.

In this case the journal was of cast-iron, running in gun-bronze bearings, and was in very good, but not in the very best possible, condition. As will be seen, much better figures may be obtained. The oils were here supplied intermittently, but frequently, in the usual manner, and the results may be assumed to be substantially the same as with continuous feed. The first series were not all fresh; the second set were fresh and pure.

To show how these figures were obtained, the results are given below in detail and in the usual tabular form, as obtained by the Author by trial of a good sample of winter-bleached sperm-oil. It should be remembered that precise agreement between two tests of even the same oil, under nominally the same conditions, never can occur except by a rare accident, as the oil itself is never precisely alike throughout—sperm-oil, for example, varying in quality with its purity and age, and with

the age, sex, health, and habits of the fish from which it was taken, etc., and the conditions of the journal and the other circumstances affecting the trial can rarely if ever be duplicated with absolute precision. These differences are not usually of practical importance, but the precaution is always taken to compare each oil tested with a standard pure sperm, carefully preserved, to be tested immediately before or immediately after the test of the oil to be examined. The quantity of oil here adopted was 332 milligrammes—enough to flood the journal at one application.

DETAILS OF TEST.

Best Winter-bleached Sperm Oil.

First Trial.

Amount used upon the journal...332 milligrammes.
Speed of rubbing surface...736 ft. (224 m.) per minute.
Pressure per square inch and per cm...8 lbs. (0.56 kgs).
Total pressure...30 lbs. (13.6 kgs.).

Time.	Temperature of Brasses.	Friction, lbs.	Coefficient of Friction.	Time.	Temperature of Brasses.	Friction, lbs.	Coefficient of Friction.	Time.	Temperature of Brasses.	Friction, lbs.	Coefficient of Friction.
	Deg. Fahr.				Deg. Fahr.				Deg. Fahr.		
At Start. min.	75	0		39	160	3.5		79	190	5.5	
1	85	8		41	160	3.5		81	190	5.5	
3	120	7.5		43	163	3.5		83	195	5.5	
5	145	5.5		45	163	3.5		85	195	5.5	
7	160	5.5		47	163	3.5		87	200	5.75	
9	170	6		49	165	3.5		89	200	5.75	
11	178	6		51	165	3.5		91	205	6.5	
13	185	6		53	165	3.5		93	210	5	
15	190	5		55	167	4		95	205	4.5	
17	190	5		57	167	4		97	205	5	
19	193	5		59	168	4		99	197	5	
21	193	4.5		61	170	4		101	195	5	
23	190	4		63	170	4		103	195	5.5	
25	185	3		65	170	4		105	197	5.75	
27	180	3		67	170	4		107	200	6.5	
29	175	3	mini-	69	175	5.5		109	200	6.5	
31	170	3	mum.	71	175	5.5		111	212	6.5	
33	168	3	0.10	73	180	5.5		113	216	6.5	
35	165	3		75	180	5.5		115	216	6.5	
37	165	3.5		77	185	5.5		117	220	5.5	
119	220	6.5		139	235	7		159	240	7	
121	218	6.5		141	235	7		161	240	7	
123	220	6.5		143	235	7		163	240	7	
125	220	9.5		145	238	7		165	243	7	
127	220	9.5		147	238	7		167	243	7	
129	230	7.5		149	238	7		169	243	7	
131	230	7.5		151	238	7		171	244	7	
133	232	7		153	240	7		173	245	7	
135	234	6.5		155	240	7		175	250	7	*Mean*
137	234	7		157	240	7		177	260	7	0.1875

SECOND TRIAL.

Amount used upon the journal....................332 milligrammes.
Speed of rubbing surface....................736 ft. (224 m.) per minute.
Pressure per square inch....................16 lbs.
Total pressure....................60 lbs.

Time.	Temperature of Brasses.	Friction, lbs.	Coefficient of Friction.	Time.	Temperature of Brasses.	Friction, lbs.	Coefficient of Friction.	Time.	Temperature of Brasses.	Friction, lbs.	Coefficient of Friction.
At Start.	Deg. Fahr.				Deg. Fahr.				Deg. Fahr.		
min.	70	0		17	275	11.5		35	325	10.5	
1	80	15	* Minimum 0.133.	19	290	11.5		37	325	11	
3	130	10		21	305	11.5		39	327	11.5	
5	170	10		23	315	11.5		41	333	11.5	
7	200	9		25	320	11.5		43	337	12	
9	215	9		27	320	9.5		45	342	15	
11	239	9		29	320	10		47	352	12	
13	250	8*		31	318	11.5		49	355	10	
15	262	9		33	322	10.5		51	350	10	
53	350	11		59	335	10		65	318	10.5	
55	350	10		61	325	10		67	325	10	a'vge
57	340	10		63	318	9.5		68	325		0.1776

THIRD TRIAL.

Amount used upon the journal....................332 milligrammes.
Speed of rubbing surface....................736 ft. (224 m.) per minute.
Pressure per square inch....................32 lbs.
Total pressure....................120 lbs.

Time.	Temperature of Brasses.	Friction, lbs.	Coefficient of Friction.	Time.	Temperature of Brasses.	Friction, lbs.	Coefficient of Friction.	Time.	Temperature of Brasses.	Friction, lbs.	Coefficient of Friction.
At Start.	80	0		5	210	11.5	0.096 minimum.'	11	295	15 to	
1	95	21		7	235	11.5		12*	320	25	av'ge 0.1317
3	170	15		9	260						

FOURTH TRIAL.

Amount used upon the journal....................332 milligrammes.
Speed of rubbing surface....................736 ft. (224 m.) per minute.
Pressure per square inch....................48 lbs.
Total pressure....................180 lbs.

Time.	Temperature of Brasses.	Friction, lbs.	Coefficient of Friction.	Time.	Temperature of Brasses.	Friction, lbs.	Coefficient of Friction.	Time.	Temperature of Brasses.	Friction, lbs.	Coefficient of Friction.
At Start.	80	0		3	180	15	0.0833 minimum.	7	285	30 to	
1	100	20		5	235	16		8	320		av'ge
								9	345	40	0.11[illegible]4

135. The Relative Standing of Oils, such as are found in the market, as determined by their power of reducing friction, and economizing work and energy, when used on machinery in which the pressures are low, is readily determined by the study of the preceding table. The columns of minimum values of the coefficient of friction may be taken to represent the values of the oils there named when lubrication is continuous and free; and these values are those to be selected for the purposes of such a comparison.

Comparing the oils tested at any one pressure, it is seen at once that they differ greatly in their power of reducing friction at whichever pressure they are compared. All give lower coefficients as the pressure rises; but the differences are great at all pressures. The following table exhibits the relative standing of the oils named at the several pressures recorded:

RELATIVE STANDING OF LUBRICANTS.

First Series.

ORDER.	PRESSURES. [Lbs. per sq. in. and kgs. per sq. cm.]			
	8 0.56	16 1.12	32 2.24	48 3.36
1	Crude Mineral Lubricating.	Natural Whale and Cocoa-nut.	Palm.	Pea-nut.
2	Nat. Summer Sperm	Nat. W. Sperm. Ex. Neat's-foot. Tallow. Olive. Menhaden. Crude Lub.	Labrador Cod.	Olive.
3	B. S. Whale. B. W. Whale. Refined Seal. B. W. Elephant. Olive. Rape-seed. Cocoa-nut. Mineral Sperm. Bl. Deod. Min. Lub.	N. S. Sperm. Ref. Seal. B. W. Elephant.	C. P. Castor.	B. W. Elephant. Cocoa-nut.
4	N. W. Sperm. N. S. Whale. Ex. Neat's-foot. Tallow. Pea-nut. Lab. Cod. Deod. W. Min. Lub. Unbl. W. Min. Lub.	C. P. Castor.	N. W. Whale. Tallow.	Labrador Cod.

RELATIVE STANDING OF LUBRICANTS—*Continued.*

Order.	Pressures. [Lbs. per sq. in. and kgs. per sq. cm.]			
	8 0.56	16 1.12	32 2.24	48 3.36
5	Cotton-seed.	W. Lard.	Cocoa-nut. Mineral Sperm.	Palm.
6	B. W. Sperm.	Ref. Cotton-seed.	N. S. Sperm. Rape-seed. Elaine. Cocoa-nut. Tanner's Cod.	Cotton-seed.
7	Menhaden.	N. W. Whale. Cotton-seed. Palm. Rape-seed. Lab. Cod.	B. W. Sperm. Ex. Neat's-foot. Ref. Seal.	B. W. Whale.
8	W. Lard. Palm. Ref. Cotton-seed.	B. W. Sperm.	Menhaden.	N. S. Whale. Rape-seed. C. P. Castor.
9	N. W. Whale.	B. W. Whale. Pea-nut. Paraffine.	B. W. Whale. Winter Lard. Olive. Ref. Cotton-seed.	N. W. Sperm. W. Lard. Ref. Seal.
10	B. W. Whale.	Mineral Sperm.	Cotton-seed.	Ref. Cotton-seed.
11	N. S. Whale. Ex. Neat's-foot. Tallow. Pea-nut. Lab. Cod. Deod. W. Min. Lub. Unbl. W. Min. Lub.	Elaine. Rosin. Tanner's Cod. Deod. W. Min. Lub. Bl. W. Min. Lub. Unbl. W. Min. Lub.	N. S. Whale.	Tanner's Cod.
12	Cotton-seed.	....	N. W. Sperm. W. Lard. Ref. Seal.	Tallow. Rosin.
13	B. W. Sperm.	....	Menhaden.	B. W. Sperm. Mineral Sperm.
14	Menhaden.	....	B. W. Whale. W. Lard. Olive. Ref. Cotton-seed.	N. W. Whale. Tanner's Cod.
15	W. Lard. Palm. Ref. Cotton-seed.	....	Cotton-seed.	Tallow. Rosin.
16	N. W. Whale.	....	N. S. Whale.	B. W. Sperm. Mineral Sperm.
17	C. P. Castor.	....	Deod. W. Min. Paraffine.	N. W. Whale. Menhaden.
18	Elaine. Paraffine.	....	Bl. Deod. Min.	N. S. Sperm.
19	Tanner's Cod.	....	Unbl. Deod. Min.	Ex. Neat's-foot.
20	Rosin.	....	Crude Min.	Elaine.
21	....	....	....	Bl. Deod. Min. Deod. Min. Unbl. Min. Crude Min. Paraffine.

RELATIVE STANDING OF LUBRICANTS.

Second Series.

Order.	Pressures. [Lbs. per sq. in. and kgs. per sq. cm.]			
	8 0.56	16 1.12	32 2.24	48 3.36
1	W. P. Cotton-seed. B. W. Whale.	W. P. Cotton-seed.	Menhaden.	Ref. Rape-seed.
2	Olive. Menhaden.	N. W. Whale. Ex. Neat's-foot.	W. Lard. W.P Cotton-seed.	Olive.
3	Ex. Neat's-foot.	Menhaden.	N. W. Whale. Olive. W.P Cotton-seed.	N. W. Sperm. B. W. Whale. W. Lard.
4	W. Lard.	B. W. Whale.	Ex. Neat's-foot.	W.P.Cotton-seed.
5	Ref. Rape-seed.	Ref. Rape-seed.	B. W. Whale. Ref. Rape-seed.	N. W. Sperm. Menhaden.
6	N. W. Whale.	W. Lard.	N. W. Sperm. B. W. Sperm.	Ex. Neat's-foot.
7	...	N. W. Sperm. B. W. Sperm.	...	...

Studying these tables, a number of interesting facts are revealed. It is seen that when under moderate pressures whale-oil is better than sperm, while as pressures rise the sperm gains in value, finally excelling whale. This difference will be found still more marked under very heavy pressures. The mineral oils fall at the end of the list under pressures exceeding the lowest here given, although standing well under the minimum. As will be seen elsewhere, these light oils make excellent spindle-oils, and are good lubricants for such low pressures as are met with in the working of textiles. They vary enormously in quality, however, and the Author has met with refined petroleums which fully equal sperm under the heaviest pressures. This has since been observed by other investigators. Olive-oil stands well under all pressures here reported on, as do the other vegetable oils generally. Castor-oil is too viscous for general use, however. Tallow and neat's-foot oils are better at the lower than at the higher of these pressures; the reverse is the case with palm and cotton-seed oils.

It is to be remembered that the order of standing just determined is liable to be changed by a change of velocity or of temperature, and by alteration of pressure outside the range here given.

It was found by Mr. Woodbury that the best neat's-foot oil,

used as a spindle-oil, absorbed 3.2 times as much power as the best refined light petroleums. The mixed oils are sometimes best for heavy machinery; unmixed refined petroleum of low density is probably best for light machinery. The following are the figures obtained by test at low pressure, moderate speed, and standard temperature, the conditions being as nearly as possible those met with in spinning-frames.

COEFFICIENTS OF FRICTION FOR SPINDLE-OILS.

Order of Value.	Oil.	Coefficient of Friction at 100 Degrees, F.
9	Refined Petroleums, Heavy Spindle	0.1187
12	" " " "	0.1233
10	" " " "	0.1208
4	" " Light Spindle	0.1113
5	" " " "	0.1132
1	" " Extra Machinery	0.0756
14	Lard	0.2181
3	Bleached Winter Sperm	0.1067
11	" " "	0.1217
8	" " "	0.1170
2	" " "	0.0956
7	Unbleached Winter Sperm	0.1147
6	Bleached Winter Sperm	0.1141
13	Seal Oil	0.1608
15	Neat's-foot	0.2427

These "thin" spindle-oils cannot be used at high pressures and low speeds; heavy viscous oils only remain between the surfaces, unless carried in by rapid motion of journal.

The experiments of Mr. Beauchamp Tower, made at the request of a committee of the British Institution of Mechanical Engineers,* give several oils the following relative standing, as averages for loads from 100 to 310 lbs. per square inch (7 to 22 kgs. per sq. cm.):

COMPARISON OF OILS—RELATIVE FRICTION.

Oil.	Grease as Standard.	Sperm as Standard.
Sperm Oil	0.48	1.00
Rape-seed Oil	0.51	1.06
Mineral Oil	0.62	1.29
Lard Oil	0.65	1.35
Olive Oil	0.65	1.35
Mineral Grease	1.00	2.17

* Proceedings, 1883.

These figures are supposed by their author to represent closely the resistance, the body or viscosity, and the weight-carrying power of these unguents, the latter being considered proportional to the viscosity of the oil. It was found that the resistance of rape-seed oil, taken as an example, was one eighth as great when the journal was worked in an oil-bath as when oiled with a siphon cup, or by a pad, the coefficients being 0.0014, 0.0098, and 0.0090, respectively.

The best lubricants, as a rule, have the lowest weight-carrying power. The Author has used sperm-oil under pressures fully equal to, and even sometimes exceeding, those attainable with other oils—a result, however, which is not accordant with the experience of some other investigators.

136. **The Relative Endurance of Oils** tested on the journal used by the Author in making determinations of the coefficients of friction has been ascertained for a number of the more common lubricants. The difficulties met with in attempts to determine with even approximate accuracy the wearing power of lubricating materials have already been referred to; but only experience can enable any one to secure reliable data.

Testing a number of the oils of commerce* for durability, on a cast-iron journal, there were used 32 milligrammes at each application, and the time noted required to run the journal dry, with the following result:

OILS OF COMMERCE, AVERAGE ENDURANCE.

Pressure per Square Inch.	Running Time.			Rise of Temp., b.	Average coefficient, f.	Heat coefficient, $\frac{a}{b} = C$.
	Ave. a.	Min.	Max.			
8 lbs.	82	17	411	167° F.	0.20	0.50
16 "	29	9	97	212	0.16	0.14
32 "	10	2	19	228	0.12	0.05
48 "	8	1	13	228	0.10	0.04

The "heat coefficient" is valuable as exhibiting the relative increase of temperature per minute during the trial. Its value

* This collection included many oils of little value as lubricants.

is sometimes—usually wrongly, although in some cases nearly correctly—taken as a measure of endurançe.

Several well-known oils ran thus—the speed being 750 ft. (230 m.) per minute:

ENDURANCE, ETC., OF LUBRICANTS ON CAST-IRON.

NAME.	Lbs. per sq. in.	Running Time.	Rise of Temperature.	Coefficient, f.	Heat Coefficient, C.
Summer Sperm..	8	111 min.	230° F.	0.13	0.48
" " ..	16	29 "	225	0.10	0.12
" " ..	48	9 "	195	0.08	0.04
Lard............	8	165 "	270	0.13	0.61
"	16	33 "	215	0 11	0.15
"	48	7 "	265	0.10	0.02
Olive...........	8	83 "	170	0 13	0.48
"	16	41 "	245	0.10	0.16
"	48	14 "	240	0.06	0.05
Cotton-seed.....	8	107 "	185	0.16	0.57
" "	16	45 "	275	0.12	0.16
" "	48	12 "	310	0.07	0.03
Cod............	8	40 "	200	0.15	0.20
"	16	14 "	175	0.12	0.08
"	48	9 "	220	0.07	0.04
Crude mineral (?)	8	129 "	105	0.10	1.22
" "	16	97 "	285	0.10	0.34
" "	48	5 "	270	0.10	0.02

Comparing a mixture of plumbago and grease with sperm-oil, the former was found to have a lower coefficient, to heat up less rapidly, and to endure several times as long. It was also indicated that plumbago in very fine flakes was better than in an impalpable powder.

Testing sperm and lard oils for durability, on a small steel journal, gave:

ENDURANCE OF SPERM AND LARD OILS.

Durability of one 8-milligramme drop: Feet Run.

Pressure per sq. in......... " " " cm....	100 7	200 14	250 17.5	275 18.5
Sperm..................	7204	7685	7675	7521
Lard..................	6797	7139	7090	7008

Others of the commercial oils found in the market and largely purchased by consumers, who have no means of testing them, endure but for a very small fraction of the time and the distance travelled with sperm and lard, and the Author has rarely if ever found an oil which equals sperm in this quality.

The "Railroad Machine" has given the following for sperm and lard oils, using a much larger quantity than was taken above:

	300 lbs.	500 lbs.
Sperm, raw (ft.)........................	19 800	13.500
Lard, " "	10.557	7.515

The coefficients being at the same time,

Sperm	0.0046	0.0033
Lard	0.0059	0.0044

The journal was in this case of very soft steel, of standard size, and was driven at a speed corresponding to 30 miles an hour.

In the attempt to make use of such determinations of the endurance of lubricants in daily practice, the investigator meets with a serious difficulty which has, however, no relation to the character of the material used. It is an important fact, and one which should be constantly borne in mind, that the maximum wearing power of a lubricant, as it is here defined and determined, has no necessarily definite relation to the quantity which will be actually used, or even required, when working under other conditions.

Usually, the same amount will be used, whether it be of great or of little wearing power, the amount being usually determined by the method of feeding, rather than by its intrinsic character. Other things being equal, the more viscous lubricant will feed more slowly, and will therefore be apparently of higher wearing power than the more fluid lubricant; a grease will last longer than an oil; the method of applying the lubricant to the journal will determine whether it is economically or wastefully used. These are vastly more important facts than they are generally supposed. Regular

trains on railroads have been known to use nine times as much grease as an experimental train on which the most rigid economy was exercised.*

It thus becomes evident that the proper method of procedure is to first determine the value of the lubricant by a series of careful tests at the pressures, velocities, and temperatures. and with the kind of rubbing surfaces proposed to be used. then to find, and to adopt, that method of feeding which will insure maximum economy. As a rule, however, determinations of endurance are of comparatively little value in every-day practice, because their use is rarely, and seldom can be, regulated by their endurance; the same amount would generally be used, and the same quantity wasted, whether the wearing quality be high or low. The real value of a lubricant is therefore generally measured by its power of reducing friction.

The following are the details of a trial reported at the Brooklyn Navy Yard, in which a less certain but less troublesome method was adopted:

The oil was measured by dropping. The same quantity, five (5) drops, was used in all the tests.

When a seeming discrepancy appeared, or doubt arose regarding any result, the experiment was repeated until satisfaction was obtained. The driving power came from the Navy-Yard engine, and the speed of the testing-machine varied with the work done by the engine. Owing to this cause it was not claimed that the results were absolutely correct. The average speed was however taken, which so nearly approximates uniformity, that the data may be considered correct for all practical purposes of comparison. Two series of tests were made, one of three-minutes runs, and another of one minute each.

* *Railroad Gazette*, Sept. 20, 1878.

ENDURANCE OF SPERM AND LARD OILS.

One-Minute Runs.

Oils.	Revolutions.	Increase of heat in units of degrees Fahrenheit.	Coefficient, *c*.	Comparative efficiency, sperm being 100.
	a.	*b*.	$\frac{a}{b} = c$.	*h*.
Sperm................	1812	43 5	41.6	100
Prime Lard...........	1790	46	38.8	93.2
Lard No. 1............	1883	50	37.6	90.5
Lard No. 2....	1810	50	36.2	87.02

Three-Minute Runs.

Oils.	Total Revolutions.	Per Minute.	Increase of heat in units of degrees Fahrenheit.	Coefficient. *f*.	Comparative efficiency, sperm being 100.
	d.	*a'*.	*e*.	$\frac{d}{e} = f$.	*h'*.
Sperm................	5506	1835.3	82	67.1	100
Prime Lard...........	5741	1913.6	90	63.8	95.1
Lard No. 1............	5428	1807	90	60.3	89.8
Lard No. 2............	5500	1833	96	57.3	85.4

Columns *b* and *e* give the increase of heat in degrees (Fahrenheit) of the journal, starting from a nearly constant temperature of 78° or 80°. The unit of comparison is the number of revolutions obtained for each degree of increase in temperature, and is obtained, in the minute runs, by dividing column *a* by column *b* which gives the coefficient column *c*, $\left(\frac{a}{b} = c\right)$, and in three-minutes runs by dividing column *d* by *e*, giving the coefficient in column *f*, $\left(\frac{d}{e} = f\right)$.

Columns *h* and *h'* compare the efficiency on the basis of sperm being 100.

It need hardly be repeated here, that the ratio of heat developed to revolutions made or distance traversed has no necessary and definite relation to the real power of endurance of the oil.

The real value of a lubricant to the user is a somewhat difficult quantity to determine, since it really depends, not

upon the relative friction-reducing power and endurance, as usually assumed, but upon the value of the power saved by its use. This value varies in every case, and is affected by every variation of working conditions.

So far as the value of these oils is determined by durability, it is seen that sperm excels lard oil very greatly; it has already been seen that it also excels in power of reducing friction under the conditions of test here met with.

The first of the tables in this article shows the time of endurance of the oils to be dependent upon the pressure under which they are worked, and to decrease in a higher ratio than those pressures increase, even within the moderate range there given. The second table shows lard-oil to excel sperm, olive, cotton-seed, and the mineral oils, at the lowest pressure; while it becomes, next to the mineral oils, the lowest at the highest pressure, under which load olive-oil stands first and cotton-seed second. The change to a fine steel journal, running in bronze, and under much higher pressures, makes sperm-oil far the better when compared with lard, which result is confirmed by the navy experiments, which make sperm ten per cent better than lard.

The following illustrates the value of a crude well-oil from the Shoshone Wells, Wyoming, as compared with sperm taken as a standard.

This oil is intensely black, and the coloring matter is inseparable. On distillation there was obtained: Naphtha, 0.63; 0.47 kerosene having 159° F. flash-test; 0.32 of a neutral and light-colored lubricating oil; and 0.12 dry coke. The oil as it flows has a gravity of 20° B. Its flash-test is 294° and fire-test 322° F. (146° and 161° C.). Cold-test 16° below zero (— 27° C.). The results of tests by the Author were:

FRICTION.

Coefficient of Friction.

Name of Oil.	Pressure.		
	50 lbs. 3.5 kgs.	200 lbs. 14 kgs.	300 lbs. 21 kgs.
Sperm	0.0034	0.0051	0.0057
Black Oil	0.0077	0.0085	0.0071

Assuming sperm to be 100, the following table gives the relative value of the oils as reducers of friction:

Value in Per Cent.

Name of Oil.	Pressure.		
	50 lbs. 3.5 kgs.	200 lbs. 14 kgs.	300 lbs. 21 kgs.
Sperm...........................	1.00	1.00	1.00
Black Oil.......	0.44	0.60	0.80
Lard..........................	....	0.75	0.75

ENDURANCE.

Name of Oil.	Number of Revolutions.		Feet Travelled.	
	First Trial.	Second Trial.	First Trial.	Second Trial.
Sperm............	21.300	24.400	7.434	8,516
Black Oil,.......	11,700	12,000	4.083	4.188

Sperm taken at 100, the following represents the relative wearing power:

Value Per Cent.

Name of Oil.	First Trial.	Second Trial.	Averages.
Sperm.........................	1.00	1.00	1.00
Black Oil......................	0.55	0.49	0.52
Lard..........................	....	....	0.52

GUMMING.

	Value.
Sperm.......	10
Black Oil	6.25
Lard.........................	5.50

The following records of tests made by the Author exhibit both the methods and the results, as derived by trial of reputed pure oils. The first table illustrates the test of good lard-oil, determining its friction-reducing power and its endurance at ordinary temperatures, and its heating action under a common moderately heavy pressure. Its best work is seen to give a minimum value of $f = 0.0173$, or about one and three quarters per cent, the average for the test rising to one fourth of one

per cent with "free feed," the oil passing to the journal by the usual system of feeding through the cap of the "brass." In the endurance test the distance rubbed over at the rate of 400 feet per minute, using 8 m. g. of oil, on a journal four inches in circumference and about $1\frac{3}{8}$ inches long, was nearly 6000 feet.

Comparing these figures with those for sperm-oil, summarized in the next record, it is seen that the latter, a reputed sperm-oil, but certainly not of the highest quality, exhibits a somewhat higher coefficient, but fifty per cent. more endurance.

STANDARD LARD OIL.

Laboratory No., ——. Original Mark, "L". Source—The Manufacturer. Composition—Pure Lard Oil. Investigation—To determine Friction and Endurance. Coefficient of Friction $= \frac{\text{Reading on Arc}}{\text{Total Pressure}}$.

	Friction.		Endurance.	
No. of Test	I.	II.	III.	IV.
Pressure on journal, lbs. per sq. inch	100	100	100	100
Total pressure on journal, lbs	300	300	300	300
Amount of oil used on journal, m g.	Free feed.		8	8
Average coefficient of friction	0 0245	0.023	0.531	0.0516
Minimum " "	0.0176	0.0173	0.046	0.040
	Per minute.		Total.	
No. of revolutions	1200	1200	17,567	17,062
No. of feet travelled by rubbing surface	400	400	5.856	5,687
Elevation of temperature, max	77° F.	66°	190°	168°

Time, Minutes.	Revolutions.	Temperature, F.	Reading on Arc.	Coefficient of Friction.
Test I.—Friction.				
0	....	100°	15	
5	6.000	150°	7.8	
10	12.000	164°	6.1	
15	18,000	171°	6.1	
20	24,000	173°	5.8	
25	30,000	175°	5.5	min.
30	36,000	177°	5.3	0 0176
			Av'ge	0.0245
Test II.—Friction.				
0	....	110°	14	
5	6,000	157°	7.5	
10	12,000	169°	6.0	
15	18,000	173°	5.6	
20	24,000	174°	5.5	
25	30,000	174°	5 2	min.
30	36,000	176°	5.2	0.0173
			Av'ge	0.023
Test III.—Endurance.				
0	....	82°	16 5	
2	....	110°	17.5	
4	....	160°	21.0	
6	....	195°	22.0	
8	....	220°	23.0	
10	....	250°	19.0	
12	....	268°	17.5	
13	....	272°	22.0	
	Redistributed oil.			min.
15	....	220°	14.0	0.046
17	....	240°	16.0	
18	....	250°	20.0	
			Av'ge	0 0631
Test IV.—Endurance.				
0	....	100°	14 5	min.
2	....	130°	12 0	0.040
4	....	160°	12.5	
6	....	185°	16 0	
8	....	213°	15.5	
10	....	245°	22 5	
	Redistributed oil.			
12	....	220°	14.0	
14	....	245°	14.5	
16	17,062	268°	18	
			Av'ge	0 0516

SPERM OIL

Laboratory No., ——. Original Mark, ——. Source, ——. Composition—Reputed Sperm Oil. Investigation—To determine general value. Coefficient of Friction = $\frac{\text{Reading on Arc}}{\text{Total Pressure}}$.

	Friction.		Endurance.	
No. of Test	I.	II.	III.	IV.
Pressure on journal, lbs. per sq. inch	100	100	100	100
Total pressure on journal, lbs	300	300	300	300
Amount of oil used on journal, m. g	Free feed.		8	8
Average coefficient of friction	0.0272	0.0242	....	....
Minimum " "	0.0203	0.0193	....	....
	Per minute.		Total.	
No. of revolutions	1200	1200	28,320	24,244
No. of feet travelled by rubbing surface	400	400	9,440	8,081
Elevation of temperature, max Fahr	106°	83°	175°	205°

The same lard-oil tested as a "cylinder-oil" gives in one case, here presented, the varying coefficient of friction which gradually decreases, as the temperature rises, from $f = 0.032$ at 100° F. to $f = 0.003$, or one tenth the first value, at 350°, and which becomes $f = 0.008$ at 200° when rising and $f = 0.022$ at the same temperature when descending the scale of temperature. Repeating the test, the same general results are observed.

The elevation of temperature observed during the test, where, as in these examples, no attempt is made to control it, will be seen to follow very closely the frictional resistance. It therefore is evidently a gauge of lubricating quality which may serve to assist the judgment in rating oils by comparison when no more exact method is available.

STANDARD LARD OIL.

Laboratory No., ——. Original Mark, "L". Source—The Manufacturer. Composition—Pure Lard Oil. Investigation—To determine value as a "Cylinder Oil." Coefficient of Friction = $\frac{\text{Reading on Arc}}{\text{Total Pressure}}$.

No. of Test	I.—Rise.	II.—Fall.	III.—Rise	IV.—Fall
Pressure on journal, lbs. per sq. inch	100	100	100	100
Total pressure on journal, lbs	300	300	300	300
Amount of oil used on journal, m. g	Free feed in all tests.			
Average coefficient of friction	0.098	0.0163	0.0141	0.0953
Minimum " "	0.003	0.0043	0 003	0.004
No. of revolutions per minute	1200	1200	1200	1200
No. of feet travelled by rubbing surface	400	400	400	400
Range of temperature, max. Fahr	250°	132°	250°	150°

Time. Minutes.	Revolutions.	Temperature.	Reading on Arc.	Coefficient of Friction
Test I.—Rise.				
Not noted.	Not noted.	100°	9.5	
		110°	8.0	
		120°	7.0	
		130°	6.0	
		140°	4.9	
		150°	4.3	
		160°	3.8	
		170°	3.3	
		180°	3.0	
		190°	2.8	
		200°	2.5	
		210°	2.2	
		220°	2.1	
		230°	2.0	
		240°	1.9	
		250°	1.8	
		260°	1.6	
		270°	1.5	
		280°	1.4	
		290°	1.3	
		300°	1.2	
		310°	1.1	
		320°	1.0	
		330°	1.0	
		340°	1.0	min.
		350°	0.9	0.003
			Av'ge	0 090
Test II.—Fall.				
Not noted.	Not noted.			min.
		340°	1.3	0.0043
		330°	2.0	
		320°	2.3	
		310°	3.5	
		300°	4.8	
		290°	5.3	
		280°	5.5	
		270°	5.6	
		260°	6.0	
		250°	6.2	

Time. Minutes.	Revolutions.	Temperature.	Reading on Arc.	Coefficient of Fricti'n
Not noted.	Not noted.	240°	6.0	
		230°	6.2	
		220°	6.2	
		210°	6.3	
		208°	6.5	
			Av'ge	0.0163
Test III.—Rise.				
Not noted.	Not noted.	100°	14.5	
		110°	11.5	
		120°	9 8	
		130°	8.7	
		140°	7.9	
		152°	7.2	
		160°	6.5	
		170°	5 5	
		180°	4.8	
		190°	4.1	
		206°	3.7	
		220°	3.0	
		240°	2.3	
		260°	1.9	
		280°	1.7	
		300°	1.3	
		320°	1.1	
		340°	1.0	min.
		350°	0.9	0.003
			Av'ge	0.0141
Test IV.—Fall.				
Not noted.	Not noted.			min.
		340°	1.2	0.004
		320°	1.6	
		300°	1.9	
		280°	2.6	
		260°	3.0	
		240°	3.6	
		220°	3.8	
		200°	4.3	
		180°	4.9	
			Av'ge	0.0953

SAMPLE OF GRAPHITE OIL.

Laboratory No., ——. Original Mark, ——. Source, ——. Composition—Heavy Mineral Oil. Plumbago in Suspension. Investigation—To determine real value of the Oil. Coefficient of Friction $= \dfrac{\text{Reading on Arc}}{\text{Total Pressure}}$.

	Friction.		Endurance.	
No. of Test	A.	B.	A.	B.
Pressure on journal, lbs. per sq. inch	100	100	100	100
Total pressure on journal, lbs	300	300	300	300
Amount of oil used on journal, m. g.	Free feed.		8	8
Average coefficient of friction	0.029	0.0312	0.0626	0.063
Minimum " "	0.018	0.0206	0.0416	0.04
	Per minute.		Total.	
No. of revolutions	1200	1200	17,000	15.210
No. of feet travelled by rubbing surface	400	400	5,666	5,070
Range of temperature, max. Fahr	107°	103°	194°	148°

MINERAL CYLINDER OIL AND GRAPHITE.

Laboratory No., ——. Original Mark, ——. Source, ——. Composition—Heavy Petroleum and Graphite in proportions not given. Investigation—To determine value as Cylinder Oil.

Coefficient of Friction $= \frac{\text{Reading on Arc}}{\text{Total Pressure}}$.

No. of Test	I.—Rise.	II.—Fall.	III.—Rise	IV.—Fall
Pressure on journal, lbs. per sq. inch	100	100	100	100
Total pressure on journal, lbs	300	300	300	300
Amount of oil used on journal, m. g	Free feed in all.			
Average coefficient of friction	0.0208	0.0099	0.0221	0.00997
Minimum " " at 350°, 340°, 330°, 320°	0.0043	0.0050	0.0043	0.0050
No. of revolutions per minute	1200	1200	1200	1200
No. of feet travelled by rubbing surface per minute	1200	1200	1200	1200
Range of temperature, max. Fahr.	260°	145°	250°	130°

Similar tests of a mineral oil containing graphite in suspension, as above given, show that the latter may be so mixed as to give an excellent result, while retaining the peculiar qualities of the plumbago-oils. The endurance above recorded is about that of lard-oil; while the best values of f are those of the best mineral and sperm oils under similar conditions.

The mixing of mineral and animal oils yields, in some cases at least, unexpected results. Thus a mineral oil, rich in paraffine, being compared with lard-oil by the Author, gave the following, under 100 lbs. pressure per square inch:

	f.	Values.
Mineral Oil	0.0150	100
Lard Oil	0.0160	0.94
Mineral, 95; Lard, 5	0.0120	127
" 90; " 10	0.0140	107

In endurance these oils stand:

Mineral Oil	100
Lard Oil	120
Mineral, 95; Lard, 5	125
" 90; " 10	160

Combining the two values, for a total relative standing, gives:

Mineral Oil	100
Lard Oil	113
Mineral, 95; Lard, 5	160
" 90; " 10	171

The introduction of graphite does not always increase either the endurance of an oil or its friction-reducing power, but probably always gives increased safety against "cutting"

or abrasion, either as an effect of higher pressure or excessive temperature. It is often difficult to secure a permanent mixture.

A mixed oil, mainly heavy petroleum, was compared by the Author with lard, pure, but of ordinary quality only, on the same journal and under as nearly as possible identical conditions, with the results given in the succeeding tables. The mineral oil, tested by variation of temperature, congealed at 10° F. (− 12°.2 C.), melted at 24° F. (− 4°.4 C.), flashed at 480° F. (249° C.), and took fire at 540° F. (292° C.). It was perfectly neutral, exhibiting no acid reaction even when heated to the point of decomposition. The minimum values of *f*, as given in these tables, may be taken as the real gauge of the value of the oil; since the best conditions should usually be maintained, as a matter of economy, whatever the quantity of oil demanded to give them. This oil excelled lard oil 10 per cent. in its friction-reducing power, and had considerably more than double the endurance of the latter; as a cylinder-oil it was vastly superior, also, at high temperatures, such as are met with in steam-cylinders.

CYLINDER OIL.

Laboratory No.. X. Origin l Mark. L Source—Manufacturer. Composition—Heavy Petroleum and and Animal Oil. Investigation—To determine Friction and Endurance. Coefficient of Friction = $\frac{\text{Reading on Arc}}{\text{Total Pressure}}$.

No. of test	1	2	3	4
Pressure on journal, lbs. per sq. inch	100	100	100	100
Total pressure on journal, lbs	300	300	300	300
Amount of oil used on journal, m. g	Free feed.		8	8
Average coefficient of friction	0.0218	0.0218	0 0495	0.0455
Minimum coefficient of friction	0.0178	0 0178	0.0318	0.0328
	Per minute.		Total.	
No of revolutions	1,200	1,200	27,200	30,120
No. of feet travelled by rubbing surface	400	400	9,060	10,040
Range of temperature, max. Fahr.	60°	64°	174°	165°

CYLINDER OIL (SAME).

Composition—Heavy Petroleum and Animal Oil. Investigation—To determine value as a Cylinder Oil. Coefficient of Friction = $\frac{\text{Reading on Arc}}{\text{Total Pressure}}$.

No. of Test	I. Rise.	II. Fall.	III. Rise	IV. Fall.
Pressure on journal, lbs. per sq. inch	100	100	100	100
Total pressure on journal, lbs	300	300	300	300
Amount of oil used on journal, m. g		Free feed in all cases.		
Average coefficient of friction	0.00718	0.00715	0 012	0 008
Minimum coefficient of friction	0.0035	0.0038	0.0035	0.0036
No. of revolutions per minute	1,200	1,200	1,200	1,200
No. of feet travelled by rubbing surface, per minute	400	400	400	400
Elevation of temperature, max. Fahr	260°	170°	260°	170°

137. Pressure modifies Friction to a very important extent, as is seen plainly in the tables already given of coefficients of friction of the commercial oils. The general effect is to reduce the coefficient of friction rapidly, as pressures increase in intensity, until a minimum is reached, passing which the coefficient still more rapidly increases, until abrasion and "cutting" take place, causing frequently serious injury of the machine and great waste of power.

The next three tables exhibit this fact quite as strikingly as the preceding. It presents the results of the experiments of the Author at pressures rising to 1000 lbs. per sq. inch (70 kgs. on the sq. cm.), and upon both a cast-iron journal, as in the first set, and upon a steel journal in more perfect condition.

On examination of the tables given in Article 134, we are at once impressed with the immense difference which occurs with variation of pressure. It is seen that, at a pressure of 48 lbs. per square inch (3.36 kgs. per sq. cm.), the values are not far from those quoted by accepted earlier authorities, but at the lower pressures, where the resistance is due more to viscosity than to true friction, the value of the coefficient of friction immensely exceeds those familiar values. It is instructive to compare these figures with those obtained at high pressures, with which object we give the table below. Tested on a fine steel journal, with free lubrication, the figures become but a fraction of those already given. Sperm, lard, and West Virginia oil, thus tested by the Author, give:

COEFFICIENT OF FRICTION ON FINE STEEL JOURNALS.

NAME.	Pressure: Lbs. per square inch. / Kilos. per square cm.								
	4 0.56	10 0 9	25 1.75	150 10.5	200 14	250 17.5	275 12.3	300 21	500 35 0
Sperm	0.12	0.08	0.041	0.0090	0.0096	0.0086	0.0091	0.0046	0 0033
Lard	......	......	0.056	0.0136	0.0127	0.0110	0.0090	0.0059	0.0044
West Virginia	......	......	......	0.0120	0.0095	0.0081	0.0100	....	....

The experiments of Mr. Woodbury* give the method of variation of the figures for still lower pressures, thus:

Pressure:	Lbs. per sq. inch..	1	2	3	4	5
	" " cm...	0.07	0.14	0.21	0.28	0.35
Values of f....	....	0.38	0.27	0.22	0.18	0.17

These values of the coefficient of friction of motion were obtained on new surfaces at a temperature of 100° F. (38° C.), and at a velocity of 600 feet per minute. The surfaces were probably not quite equal to those just described, or the lubricant may not have been equally good; the figures are considerably higher.

Here it is seen that the figures are as widely different from accepted values at high pressures as at low, but that the difference is upon the other side. At those pressures, therefore, which are most used in heavy machinery the resistance of friction is vastly less than we have been led to suppose, while the friction of very light machinery is very much greater. The fact that the journals here used were of steel, instead of iron in the first case, does not modify these conclusions. Steel, cast iron, and wrought-iron all give very nearly the same figures up to their limits of pressure, when well worn.

The next table exhibits the results of experiment up to still higher pressures, and with other journals and bearings:

COEFFICIENTS OF FRICTION, OF MOTION, AND OF REST.

(*a*.)—Cast Iron Journal and Steel Boxes.

Pressures per sq. cm.	Pressures per sq. inch.	B. W. Sperm. At 150 Feet per Minute f.	B. W. Sperm. At Starting f'.	B. W. Sperm. At Instant of Stopping f''.	West Virginia. At 150 Feet per Minute f.	West Virginia. At Starting f'.	West Virginia. At Instant of Stopping f''.	Lard. At 150 Feet per Minute f.	Lard. At Starting f'.	Lard. At Instant of Stopping f''.
3.5	50	.013	.07	.03	.0213	.11	.025	.02	.07	.01
7.0	100	.008	.135	.025	.015	.135	.025	.0137	.11	.0225
17.5	250	.005	.14	.04	.009	.14	.026	.0085	.11	.016
35.0	500	.004	.15	.03	.00525	.15	.018	.00525	.10	.016
52.5	750	.0043	.185	.03	.005	.185	.0147	.0066	.12	.02
70.0	1,000	.009	.18	.03	.010	.18	.017	.0125	.12	.019
(*b*.)—Steel Journals and Brass Boxes.										
35.0	500	.0025						.004		
70.0	1,000	.008						.009		

Temperature in all cases less than 115° Fahrenheit. Velocity of rubbing, 150 feet per minute.

	W. B. Sperm.	Lard.
Ratio of $\frac{b}{a}$ =	.75 for 500,	.77
Ratio of $\frac{b}{a}$ =	.888 for 1000,	.90

* Proc. N. E. Cotton Man. Assoc., 1880, p. 61.

Studying this table, we see that with these oils the coefficient in these cases rapidly diminishes with increase of pressure, until a pressure of over 500 lbs. per square inch (35 kgs. per sq. cm.) is attained; the coefficient, after passing a pressure of probably 600 to 800 lbs. per square inch (42 to 56 kgs. per sq. cm.), increases, and at 1000 lbs. (703 kgs.) becomes about equal to that obtained at 100 lbs. (7 kgs. per sq. cm.). It will be remembered that 500 or 600 lbs. pressure (35 to 42 kgs. per sq. cm.) is usually considered to be a limit not to be exceeded in general practice in machine construction.

Nevertheless, it is not uncommon to find as high pressures as 1000 or even 2000 lbs. (703 to 1406 kgs. per sq. cm.) in the crank-pins of steam-engines. In such cases, however, the pins are almost invariably of steel, and the journals of good bronze —conditions which are less seldom met with elsewhere. There is also in this case, as wherever a "reciprocating force" acts to move a piece, a condition which permits higher pressures to be successfully worked than can be reached elsewhere; the alternate application and relief of pressure occurring between journal and bearing at each change of direction of the driving-force causes a release, at such times, which permits the oil to find its way between the rubbing surfaces, and its expulsion is not then fully effected before the succeeding relief of pressure again permits its renewal. A somewhat similar action is consequent upon the rise and fall of a locomotive or of a railway-car on its springs as it rapidly traverses even a smooth track. Where this relief cannot take place, the limit of pressure is earlier met. In exceptional cases, of very slow motion, or of quickly relieved pressure, as in cotton-presses, the limit is higher, sometimes six or seven times the higher figure, above.

138. The Law of Variation of Friction with pressure may be approximately determined from the above. Referring to the last table, it is seen that between 100 and 750 lbs. the value of the coefficient may be obtained approximately by the expression $f = \frac{a}{\sqrt{P}}$, in which a is a constant quantity and P is the pressure in pounds per square inch; for sperm-oil

$a = 0.080$, for crude heavy mineral oil $a = 0.150$, and for lard-oil $a = 0.125$.* For a wider range the rather less handy expression,

$$f = \frac{a}{P^{\frac{1}{3}}},$$

may be adopted, making a from 0.25 to 0.40. No such expressions can be accepted as general; they are purely artificial, and only applicable under the conditions of observation upon which they are based. It will presently be seen that the law is modified by temperature and speed.

The following data were given by trials of two excellent kinds of grease, and of sperm-oil, compared with them as standard.

COEFFICIENTS OF FRICTION OF GREASES.

Steel Journals; Bronze Bearings. Velocity, 300 ft.

LUBRICANT.	Pressure: Lbs. per sq. in. / Kgs. per sq. cm.					Average.
	100 7	200 14	300 21	400 28	500 35	
Sperm Oil......	0.0141	0.0063	0.0049	0.0042	0.0039	0.0067
Grease, No. 1...	0.0249	0.0146	0.0125	0.0105	0.0114	0.0140
" No. 2...	0.0188	0.0198	0.0160	0.0146	0.0175	0.017

Their relative average values in reducing friction stand, therefore: Sperm, 100; No. 1, 44.8; No. 2, 37.7: which figures would also represent their relative money values if estimated on that basis simply.

The method of variation with pressure already noted is here again illustrated, although the mathematical expression has a different set of constants, and the variation at this speed is more nearly as the inverse ratio of the cube-root of the pressure.

It was also concluded by Hirn, as a deduction from his experiments on lubricants, that the resistance varies as the square root of the pressure.

* These facts and deductions were published originally in a paper prepared in the spring of the year 1878, and read at the St. Louis meeting of the American Association for the Advancement of Science.

In the table is presented a set of values of the coefficients of friction, of motion, and of rest which are both new and important. In the columns headed "At 150 feet per minute" are given the coefficients of friction at the several pressures as obtained when the rubbing surfaces are in motion at that relative velocity. These are the common and most usually required figures. We have in the other columns, however, values which are seen at a glance to be immensely greater, and of which the values vary by an entirely different law.

The first set, "At starting," are the well-understood coefficients of friction of rest, varying with the pressure and with the nature of the unguent from 0.07 to 0.18. These values had never been determined before in this manner, and possess great importance, not simply intrinsically, but also as throwing some light upon the effect of motion upon the efficacy of lubrication. It is seen that they increase with the pressure, instead of diminishing, as do the coefficients of friction of motion, and that at the highest pressures their values become from ten to forty times the corresponding values of the latter.

In the effort required to move heavy machinery, vastly greater force is demanded to overcome friction at the instant of starting than after motion has once commenced.

The method of variation of the coefficient for rest is seen, by reference to the table, to be such that their numerical values may be approximately estimated, for the cases here considered by the formula,

$$f' = a' \sqrt[5]{P};$$

in which $a' = 0.02$ for sperm and heavy mineral oil, and $a' = 0.015$ for lard-oil.

The figures in the columns headed "At instant of stopping" were given while the machine was rapidly coming to a stop, after the driving-belt had been shifted to the loose pulley. They are, as would be expected, intermediate in value between the other figures, and have apparently no practical importance. They may be taken as constant at all pressures. Even these figures are probably higher than those sometimes reached with old journals which have been kept in good order many months

or years, and which have worn to that remarkable mirror-like smoothness which is familiar to every experienced mechanic. Values, on the "railroad machine," have been, for sperm, and even for lard, as low as one fourth of one per cent., at pressures of less than 500 lbs. per square inch; while cylinder lubricants, applied to bearings heated to the temperature of steam at 100 lbs. pressure, have given coefficients as low as one ninth of one per cent., and flooded journals with the oil-bath have even done better than this.

Later experiments, to be described, show that, as has been already indicated (§ 135), the most perfect lubrication attainable sometimes gives values of the cofficient varying nearly inversely as the pressure, and making the total frictional resistance nearly independent of pressure. Intermediate conditions give intermediate methods of variation.

The general conclusion that the coefficient of friction decreases with increasing pressure must evidently be qualified by the undoubted proposition that, with any given condition of the rubbing surfaces, and with all other conditions unchanged, there must always be ultimately reached a point at which, with increasing pressures, the limit of bearing power is attained or approached, and the friction must exhibit a change of law, the coefficient increasing, beyond that limit, as the intensity of pressure is augmented. The safe limit has been given in § 127, when considering size of journals.

The method of variation of the friction of lubricated surfaces with variation of pressure is also well shown by Fig. 45, representing results given by Mr. Waite. The experiments illustrated were made at a temperature of 100° F. (48° C.). Here, paraffine oil (light spindle-oil) is seen to offer increasing resistance with increasing pressure, at a nearly uniform rate, but with a decreasing coefficient, until a pressure of 22 lbs. per square inch (1.5 kgs. per sq. cm.) is reached, when the coefficient becomes nearly constant, the total resistance increasing very nearly as the pressure.

Lard-oil exhibits a similar "critical point," at about 40 lbs. (2.8 kgs.), and sperm at about 72 lbs. per square inch (5 kgs. per sq. cm.); while neats-foot oil has no such point

within the limits of the diagram. In each case, the decrease of the coefficient is shown by the parabolic form of the curve,

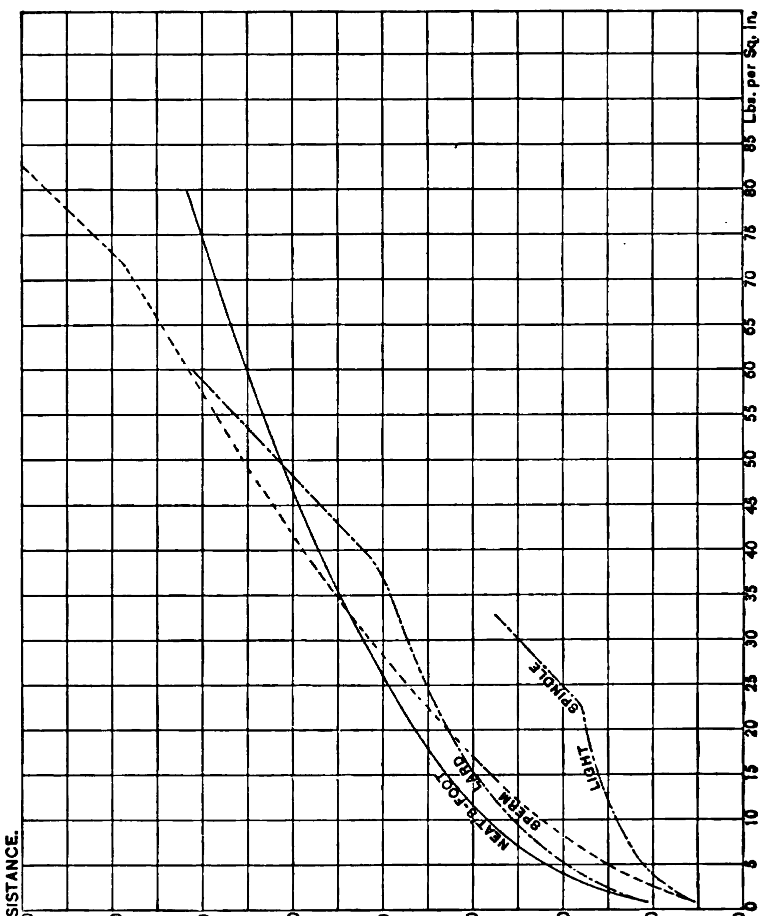

FIG. 45.—FRICTION AND PRESSURE.

which would become a straight line were the coefficient constant, or would exhibit a reversed curvature were the coefficient to increase with pressure.

Fig. 46 exhibits the same change, as observed by Woodbury, at low pressures and at various temperatures, the range falling below 5 lbs. per square inch (0.35 kgs. per sq. cm.), and between 70° and 120° F. (21° and 49° C.), the speed remaining constant.

Experiments made for the Author at various times,* on the machine designed by him and already described, have been collated and are graphically represented in Fig. 47, in which the curves exhibit the method of variation of friction with pres-

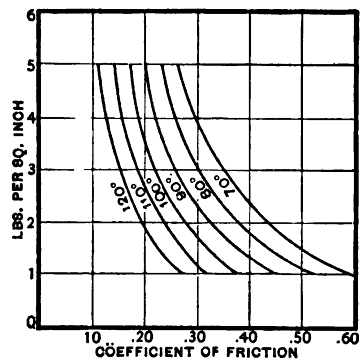

FIG. 46.—FRICTION AND PRESSURE.

sure under ordinary conditions of lubrication, at various speeds of rubbing, from 30 to 1200 feet (9 to 366 m.) per minute.

It is found that at the lowest speed the effect of variation of pressure is very similar to that at higher speeds at temperatures not differing far from those common in machinery, but that the effect is very different, and somewhat peculiar, at higher temperatures. At the lower temperatures the coefficient decreases with great rapidity at first, passes a minimum at usually not far from 100 lbs. per square inch (7 kgs. per sq. cm.), and again rises, although but slowly, as the pressure is increased to 200 lbs. (14 kgs. per sq. cm.), the change occurring very regularly.

The minimum here observed is carried to higher pressures as the speed of journal and the efficiency of lubrication are in-

* Friction and Lubrication, 1879. etc.

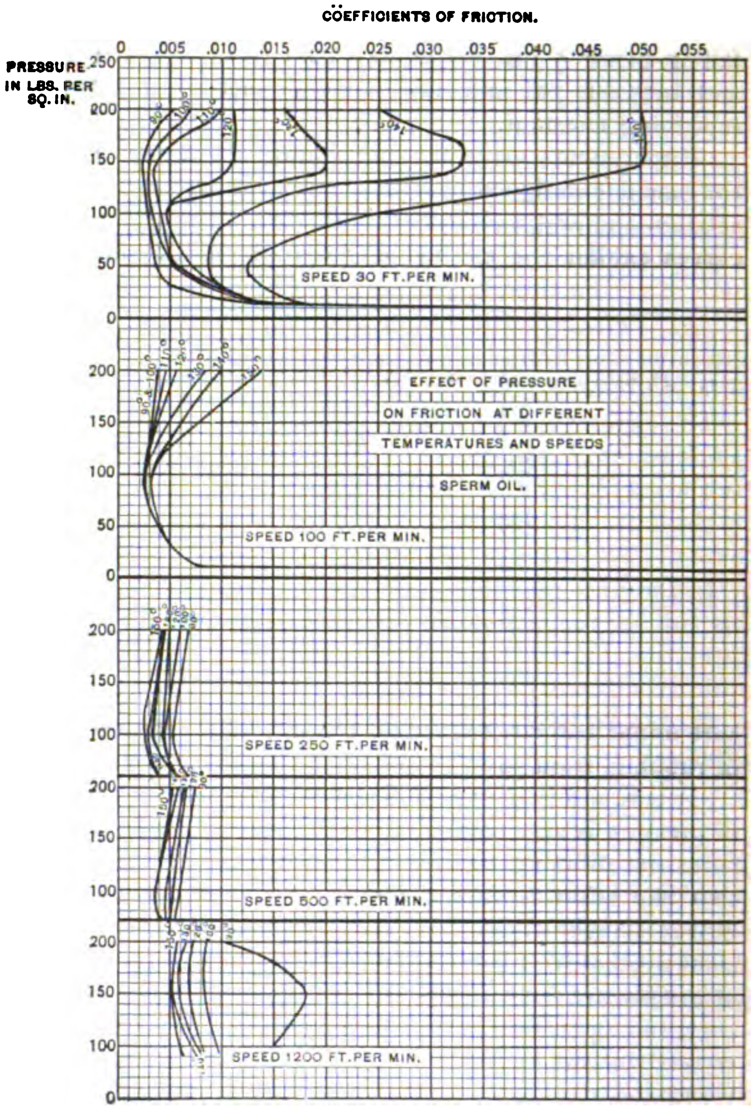

FIG. 47.—PRESSURE *vs.* FRICTION.

creased, and has been reached in experiments made by the Author, in some cases, at very much higher figures than those here given; the best figures attained being $f = 0.0025$ at various times, with the ordinary system of oiling, and at pressures ranging, with sperm-oil, from 100 to 500 lbs. per square inch (7 to 35 kgs. per sq. cm.), according to state of the journal and conditions of working. Oil-bath lubrication is found, at high speeds of journal, to carry the minimum beyond the working range of pressure, and to bring the coefficient down to a minimum of not far from one tenth of 1 per cent.

139. **Velocity of Rubbing** is an important element in determining the loss of work and energy by friction, where the surfaces are lubricated.

The experiments of Poirée and Bochet * show that between velocities of 900 and 3600 feet (270 and 1080 metres) per minute the coefficient of friction of brakes and of wheels skidding on the rails diminished very greatly—approximately from 0.2 to 0.13. The surfaces were not lubricated.

In the year 1858, Mons. H. Bochet presented his paper on this subject to the French Academy of Sciences, in which he states that he had found the coefficient of friction between surfaces of iron to be variable, diminishing as velocity increased.

M. Bochet proposed what was equivalent to the following formula:

$$f = \frac{a + bcv}{1 + bv},$$

in which f is the coefficient of friction, and a, b, and c are constants; v is the velocity of sliding in metres (or the velocity in feet divided by 3.28) per second. The values of these constants were (no lubrication):

$a = 0.3$ to 0.2 for dry and 0.14 for moist surfaces;
$b = 0.03$ for wheels and 0.07 for skids on rails;
$c =$ undetermined, but taken as negligable.

* Mem. de la Soc. des Ing. Civ., 1852, p. 110, etc. *Comptes Rendus*, xlvi. (1858), p. 802, and li. (1860) p. 974.

Prof. Kimball * determined the following table of coefficients for pine sliding on pine (dry), and deduced the conclusions:

(1) At a given inclination, the friction decreases with increasing velocity, at first rapidly, then more slowly.

(2) At the same velocity, the friction is greater the greater the angle of the sliding plane.

(3) The value of the coefficient tends to become constant.

(4) The value of this constant seemed to be the same for all experiments.

COEFFICIENTS OF FRICTION.

PINE ON PINE.

Pressure, 1¾ *lbs. per square inch* (0.12 *kg. per sq. cm.*).

Velocity per Second.		Values of Coefficient.			
ft.	m.	1	2	3	4
4	1	0 260	0.273	......	......
10	3	0.252	0.261	0.270	0.280
20	6	0 243	0 248	0.264	0.260
30	9	0 237	0 242	0.256	0.250
40	12	0.233	0.236	0.240	0.242
50	15	0.230	0.232	0 235	0 236
60	18	0.228	0.230	0.231	0 232
80	24	0 224	0.226	0.226	0.225
100	31	0.222	0.223	0.221	0.222
120	37	......	0 220	0.217	......

At pressures double and five times the above, the law still held.

Later experiments † gave the following:

PINE ON PINE.

Pressure, 4 *lbs. per square inch* (0.28 *kgs. per sq. cm.*).

Velocity, inches per minute.	Coefficient of Friction.
5	0 19
11	0.21
75	0.24
100	0.25

* *American Journal of Science*, 1876.

† Ibid.

Leather on Pine.

Pressure, 4 lbs. per Square Inch.

Velocity in inches per min.	Coefficient of Friction.	Velocity in inches per min.	Coefficient of Friction.
0.79	0.41	72.50	0.22
1.58	0.43	157.50	0.27
3.94	0.45	226.80	0.33
9.98	0.46	300.00	0.36
29.14	0.475	466.00	0.38

Leather Belts on Cast-iron Pulleys.

Velocity in inches per minute.	T_2 lbs.	T_1 lbs.	C.
0.37	30	13	0.41
0.52	30	12½	0.44
1.1	30	11½	0.48
2.3	30	10½	0.53
4.4	30	9½	0.58
15.4	30	6½	0.78
34.1	30	5½	0.86
80.3	30	4½	0.96
228.8	30	4¼	1.50

Same.—Repeated at Higher Speeds.

18	..	..	0.82
92	..	..	0.93
660	..	..	1.00
1190	..	..	0.96
1980	..	..	0.82
2669	..	..	0.69

The values of C are relative, and are not the absolute values of the coefficients of friction. With a wrought-iron shaft, turning in cast-iron bearings, well oiled, and a load of 66⅔ lbs. per square inch (4.7 kgs. per sq. cm.), at velocities of rubbing of 72, 272, 605, and 1320 inches per minute, the frictional resistance varied as 1, 0.60, 0.40, and 0.29; at the very low speeds of 0.007, 0.027, 0.060, and 0.132 inches per minute, the relative resistances were as 0.37, 0.51, 0.73, and 1.00.

Professors Jenkin and Ewing,* experimenting at still lower velocities—0.0002 to 0.01 foot (0.00006 to 0.0003 m.), and again

* Proceedings of Royal Society, 1876–77.

up to 0.6 foot (0.18 m.), per second—with various metals and without lubrication, found a similar law to prevail.

In Professor Jenkin's experiments at extremely low velocities, he has shown that, where there is a very great difference between the two coefficients of friction of rest and motion, the coefficient of friction decreases gradually as the velocity increases, between speeds of 0.012 and 0.6 foot (0.0036 and 0.183 metre) per minute. In cases where there is little or no difference between the coefficients of rest and motion, no difference was found at the various velocities between which he experimented. His experiments were made with a small steel spindle of 0.1 inch (2½ millimetres) diameter, carried in rectangular V notches, the pressure being constant, and due to the weight (86 lbs. = 39 kgs.) of a disk carried by the spindle and revolving with it. The more recent experiments of M. Marcel Deprez, with the disk of a dynamo-electric machine, started at very high velocity and slowly retarded by its own friction of journals and bearings, show a constantly decreasing resistance from 0.025 at 550, to 0.005 at 145 revolutions per minute, the friction remaining constant between 145 and 120 revolutions at 0.005, and then rapidly increasing as the disk comes to rest. The average value of the coefficient was 0.0013. The weight of disk and shaft was nearly two tons, and the journal was 2 inches (0.06 m.) in diameter.

These experiments show that there exists a continuity of values between the gradually varying coefficients for decreasing velocities and those obtained for statical friction.

The experiments reported by Kimball,* on journals running with lubrication under pressure of 15 to 25 lbs. per square inch (1 to 1.75 kgs. per sq. cm.), gave the following:

Velocity in m. per minute.....	0.3	1	1 5	2.1	3	4.5
Velocity in ft. per minute......	1	3	5	7	10	15
Coefficients..................	0.150	0.122	0.114	0.093	0.079	0.066
Velocity in m. per minute.....	6	9	12	18	25	31
Velocity in ft. per minute......	20	30	40	60	80	100
Coefficients..................	0.058	0.544	0.053	0.052	0.051	0.050

* *American Journal of Science*, March, 1878, p. 194.

At common, but somewhat slow, speeds he thus finds that the friction between pieces of pine-wood decreases rapidly as the speed increases. With the wrought-iron shaft of 1 inch (25 cm.) diameter, working in a cast-iron bearing, well oiled, an increase of velocity of rubbing from 6 to 110 feet (1.8 to 33.5 metres) per minute caused the coefficient of friction to fall to 0.3 of its first value. The pressure in this case was about 67 lbs. per square inch (4.7 kgs. per sq. cm.). The other experiments on lubricated journals at smaller pressures gave the opposite result.

Referring to the next table, p. 310, in which the effects of varying velocities, as well as of coincident variation of pressure and of temperature, are exhibited as given by experiments, it is readily seen that the change in value of the coefficient of friction with change of velocity is not great for machinery in which that velocity remains within usual limits, and at the usual temperature of a cool and properly-working journal. The effect of change of velocity varies, as is here shown, with change of temperature and of pressure.

Hirn's experiments indicate, as he has stated, that the friction of lubricated surfaces is affected by velocity through variation of the quantity of oil drawn between them at varying speeds. Even air becomes thus a lubricant at very high speeds, producing exceedingly low values of the coefficient. The observations of Despretz lead to the same conclusions.

For cool journals, in good condition, lubricated with good sperm-oil, and between the limits of 100 and 1200 feet (31 and 370 m.) per minute, these values may be taken for ordinary lubrication, in estimating lost work and in designing, as varying approximately as the fifth root of the velocity of rubbing, i.e., $f = a\sqrt[5]{V}$, in which a, at 200 lbs. per square inch (14 kgs. per sq. cm.), is about 0.0005 for ordinary lubrication, but may fall much lower with journals flooded by an oil-bath; in the latter case, also, the coefficient increases very nearly as the square root of the speed. Both Professor Jenkin and the Author have deduced * from the fact that the coefficient of

* Friction at High Velocities, Inst. Mechanical Engrs., 1879; Friction and Lubrication, 1879, p. 185.

COEFFICIENTS OF FRICTION.

New Journal of Steel; Bearings of Bronze; Velocity, Pressure, and Temperature Variable.

Lubricant: Standard Sperm Oil.

Speed per Minute.		9 metres, or 30 feet per minute.					30 metres, or 100 feet per minute.					75 metres, or 250 feet per minute.		150 metres, or 500 feet per min.		370 metres, or 1200 feet per minute.		
Kilog. per sq. cm. Press. lbs. per sq. in.		200 14	150 11	100 7	50 3.5	4 0.28	200 14	150 11	100 7	50 3.5	4 0.28	200 14	100 7	200 14	100 7	200 17	150 11	100 7
Cent.	Temp. Fah.																	
53°	150°	.0500	.0500	.0250	.0125	.125	.0140	.0074	.0025	.0037	.0630	.0047	.0028	.0053	.0037	.0060	.0058	.0061
60	140	.0250	.0330	.0110	.0087	.125	.0100	.0050	.0025	.0037	.0630	.0047	.0030	.0053	.0037	.0062	.0058	.0070
54	130	.0160	.0200	.0044	.0075	.125	.0087	.0041	.0019	.0037	.0630	.0047	.0030	.0053	.0037	.0065	.0062	.0075
49	120	.0110	.0110	0044	.0075	.125	.0056	.0035	.0019	.0037	.0630	.0047	.0037	.0056	.0037	.0069	.0067	.0080
43	110	.0100	.0033	0037	.0062	.094	.0044	.0033	.0019	.0037	.0630	.0050	.0044	.0062	.0050	.0075	.0075	.0087
38	100	.0075	.0028	.0031	.0056	.094	.0040	.0033	.0019	.0037	.0630	.0056	.0045	.0065	.0061	.0081	.0083	.0094
32	90	.0056	.0025	.0031	.0037	.094	.0040	.0033	.0019	.0037	.0630	.0070	.0052	.0075	.0061	.0100	.0170	.0150

friction of rest is always greater than that of motion, while the latter at low speeds steadily and constantly increases as the velocity of rubbing decreases, the conclusion that there is probably a continuous change resulting in the merging of the one in the other. Where the difference between the two coefficients is small, that of motion is nearly constant at all intermediate velocities. This conclusion is also reached by Mr. A. M. Wellington.* The Author has also found, by experiment, that the coefficient at high speeds steadily and continuously increases, and hence that there is a minimum value at some intermediate speed, the precise location of which minimum is determined by the pressure and the temperature. The experiments upon which the last table is based were made upon the same machine as those described previously, the journal of fine steel running in a good gun-bronze bearing, and in the manner described in the last chapter.

The experiments of Poirée and Bochet † show, as already stated, that increase of speed of rubbing decreases the friction-coefficient with unlubricated surfaces also; this decrease between the velocities of 900 and 3600 feet (270 and 1080 m.) being from 0.2 to 0.13, or about one third. The experiments of Galton and Westinghouse ‡ confirm this conclusion. This method of variation has not been found to have a limit with dry surfaces; but with lubrication, as above stated, the law changes at some point, and the minimum is found at a higher speed as the pressure on the rubbing surfaces increases. This latter conclusion is confirmed by later investigations.

With heavy machinery, the pressure and speed varying simultaneously, we may take as an approximately correct expression for flooded journals,

$$f = a \frac{\sqrt{V}}{p^{\frac{1}{2}}},$$

the value of a being usually between 0.015 and 0.02.

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* Trans Am. Soc. C E., 1884.

† Mem. de la Soc. des Ing. Civils, 1852.

‡ Proc. Inst. Mechan. Engs , 1879.

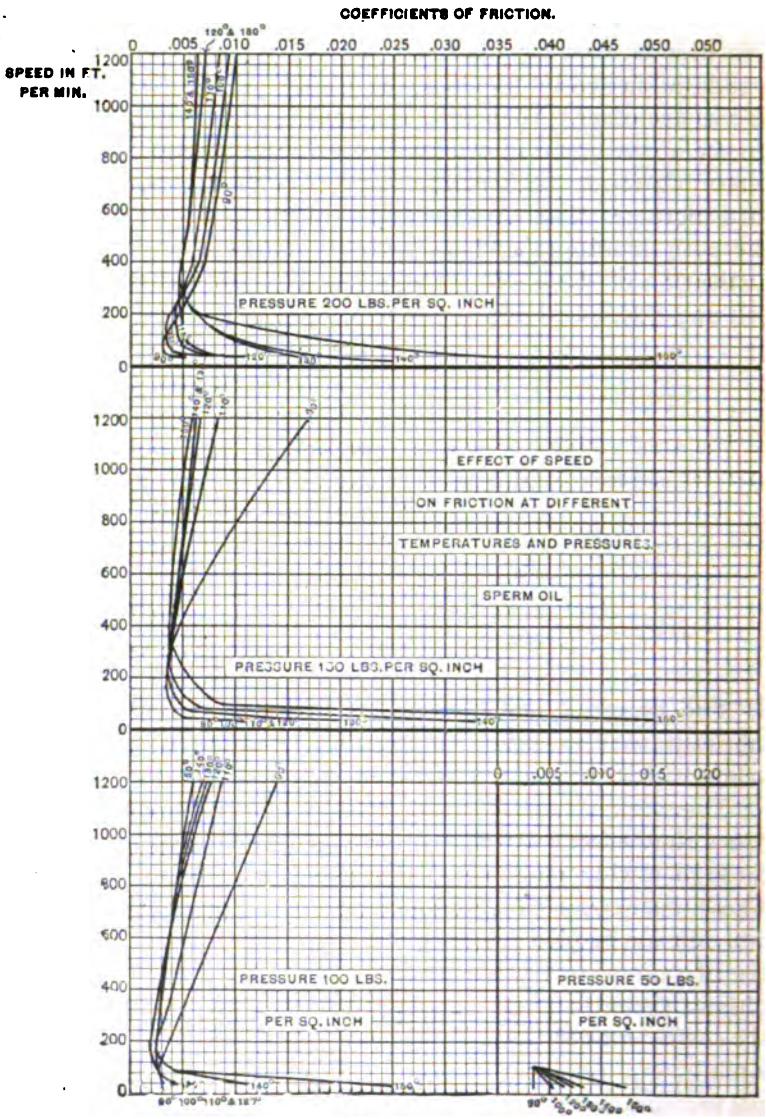

FIG. 48.—VELOCITY AND FRICTION.

With the more perfect lubrication attainable by the oil-bath the friction varies nearly as the square root of the speed, at velocities customarily met with in engineering. At very low speeds, as shown by the experiments already quoted, the coefficient decreases with increasing speed—presumably in consequence of the greater freedom of supply so secured. At speeds exceeding 100 to 150 feet (30 to 46 m.) per minute, the resistance increases slowly with ordinary lubrication, and more rapidly with more perfect oil-supply. The experiments of the Institution of Mechanical Engineers give, for oil-bath lubrication and flooded journals, approximately:

Sperm-oil . . . . $f \propto \sqrt{\frac{V}{P}}$;

Lard-oil . . . . $f \propto \frac{\sqrt{V}}{P}$;

Olive-oil . . . . $f \propto \frac{\sqrt{V}}{P}$;

Mineral-oil . . . . $f \propto \frac{\sqrt{V}}{P}$.

The apparent law thus varies with the character of the lubricant, with variation of pressure, although usually giving values of friction varying as the square root of the velocity.

The work of the Author, exhibited in Figs. 48, 49, illustrates the peculiar variation of friction with velocity of rubbing, through a wide range of speeds, pressures, and temperatures. These curves, which were constructed for the Author by the late Mr. W. G. Cartwright, indicate the existence of a definite law of variation of the coefficient, for each definite set of conditions, taken as unvarying in other respects. At low speeds the coefficient decreases, in all cases, with great rapidity; passes a minimum, usually at between 100 and 200 feet (30 and 61 m.) per minute, and then gradually increases again up to the highest speeds attained.

For sperm-oil, the increase at 100 lbs. per square inch (7 kgs. per cm.) is very uniform in these experiments, and is very

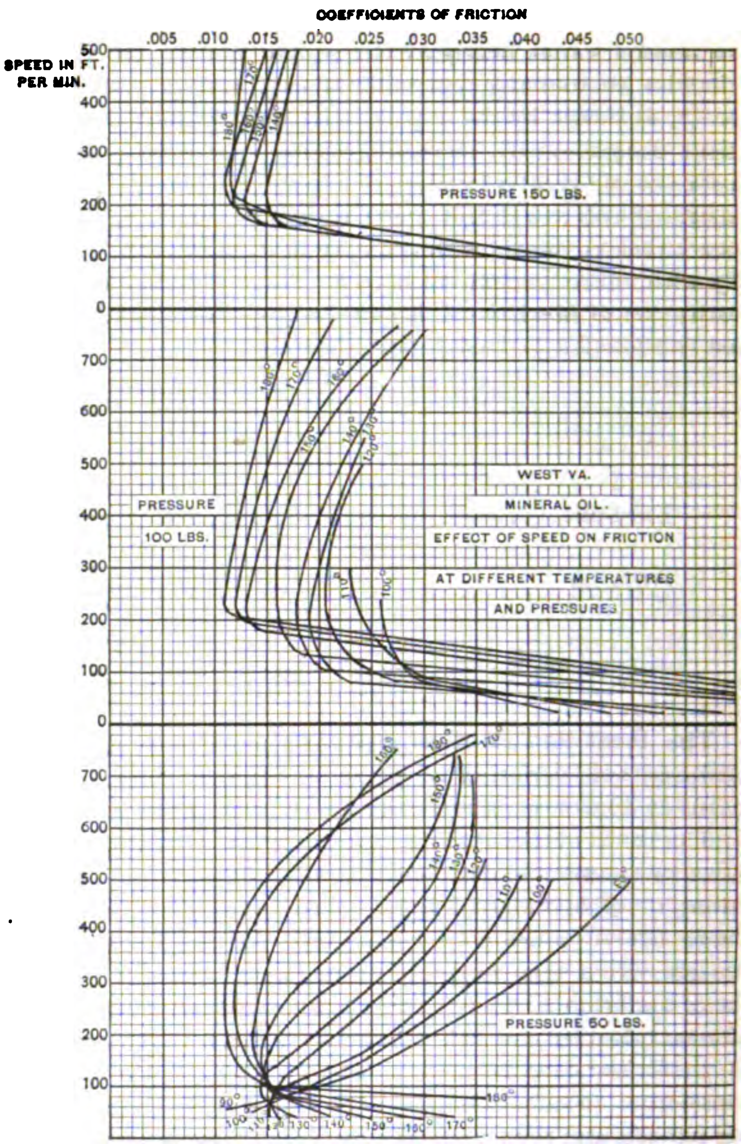

FIG. 49.—VELOCITY AND FRICTION.

nearly proportional to the increase of speed, but is most rapid at the lowest temperatures noted. The latter is the fact also at higher pressures; but less difference is usually observed with change of temperature.

Heavy petroleum, as shown in the last of these figures, exhibits the same general behavior at 100 and at 150 lbs. (7 and 10 kgs. per sq. cm.); while at the lowest pressure, 50 lbs. per square inch (3.5 kgs. per sq. cm.), the action of varying temperature becomes exaggerated to such an extent as to become very plainly observable. It is seen that with such lubrication as was here obtained the best temperature for this pressure is the highest as usual, while at 90° the coefficients steadily increase from the lowest speeds.

These curves are all established by too limited a set of observations to permit definite formulation of results, and those presented must be received and used with caution until more work is done and these laws are more completely ascertained. As confirming the general deduction that the higher speeds met with in machinery give reduced coefficients, it may be stated that Mr. Pearce, of Cyfartha, reports less indicated power required to drive an unloaded rolling-mill engine at high speeds than at low.

140. Rest and Motion, not only as already stated, give coefficients of friction differing greatly in value; but experiment indicates that they follow entirely different laws. The variations of both coefficients will probably prove to be influenced by every change of condition of surface or of method of lubrication, or of operation. Figs. 50, 51, 52, exhibit graphically the results of experiments made on the testing-machine of the Author with a wide range of pressure, and the comparison of these coefficients when using sperm, lard, and mineral oils. The temperature was in each case 115° F. (46° C.).

Under the conditions of surfaces and of lubrication—by oil-cups—here adopted, the speed of rubbing being 150 feet (46 m.) per minute, the sperm-oil (Fig. 50) exhibits a minimum coefficient at 400 to 500 lbs. per square inch (28 to 35 kgs. per sq. cm.), while the coefficient for rest rises very rapidly as pressures increase toward 100 lbs. (7 kgs.), less rapidly to 500 lbs. (35 kgs.),

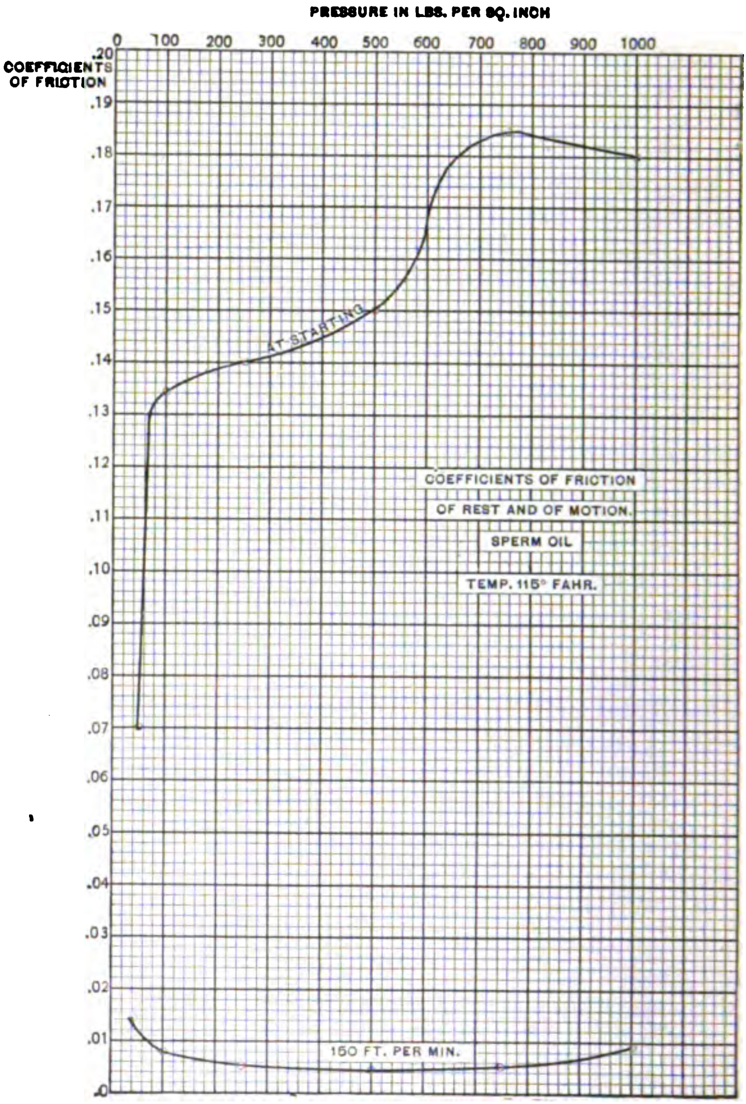

FIG. 50.—FRICTION OF REST AND MOTION.

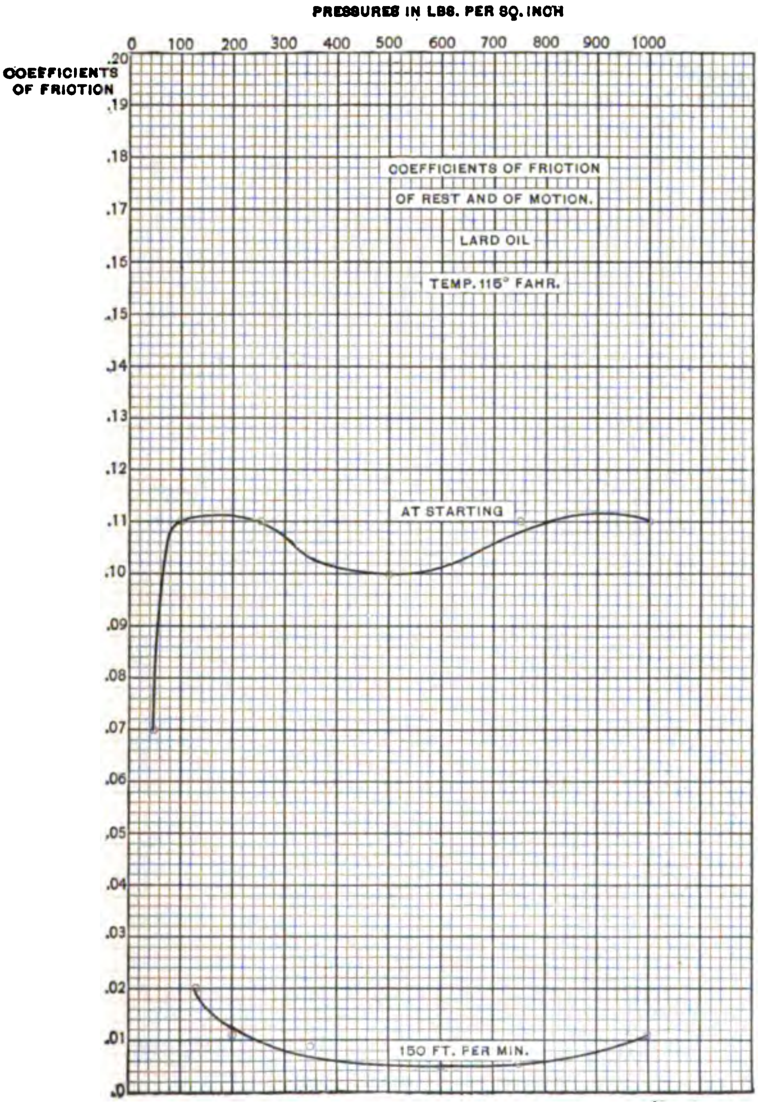

FIG. 51.—REST AND MOTION.

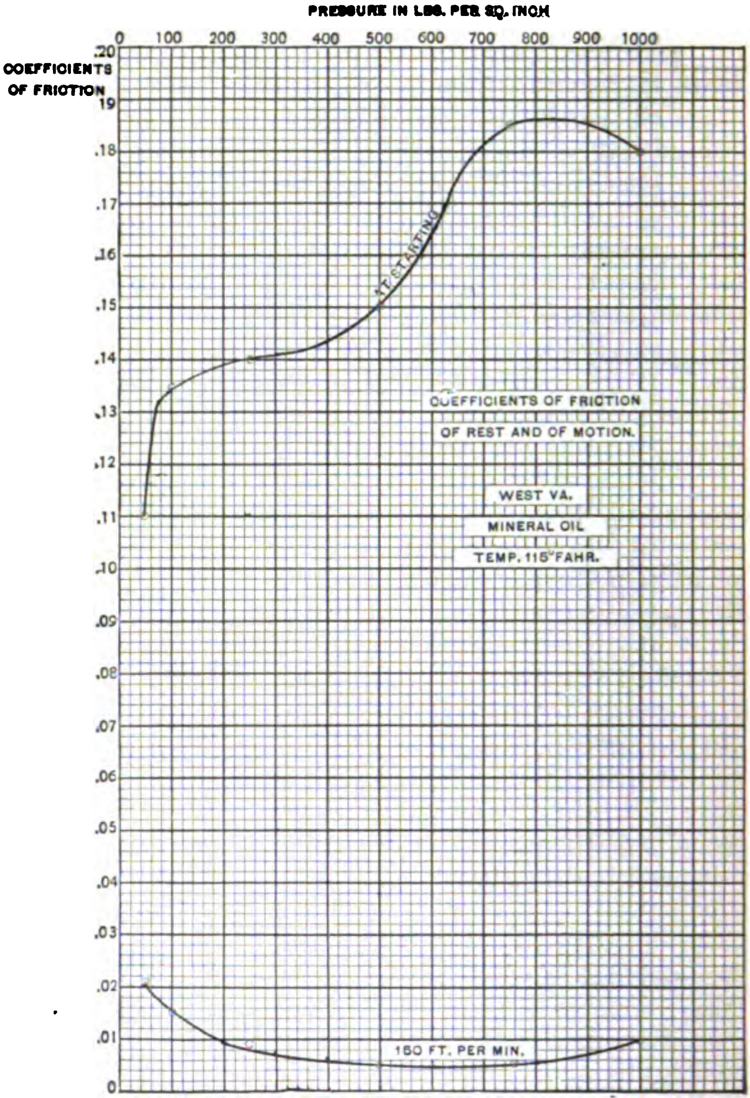

FIG. 52.—REST AND MOTION.

more rapidly again to 750 lbs. (52.5 kgs.); while the last observation at 1000 lbs. per square inch (703 kgs. per sq. cm.) gave a lower figure, which however may have been an accidental and exceptional departure from the general law.

Lard-oil (Fig. 51) exhibited the same behavior when in motion, passing the minimum at the same pressure, and having then a little higher value. The coefficient for rest also varies at the start in exactly the same manner, rapidly increasing with rise of pressure up to 100 lbs. per square inch (7 kgs. per sq. cm.) as before; but it then decreases with rising pressures, passing the maximum at about 150 lbs. (10 kgs.), and a minimum at 500 lbs. (35 kgs.), and rising to a second maximum at highest pressures.

The general character of the curve is the same as that for sperm-oil, but with the terminal portion depressed.

Heavy lubricating petroleum behaved (Fig. 52) very much like sperm-oil passing the minimum on the moving journal; at a somewhat higher figure (750 lbs.; 53 kgs.) it gives exactly the same form of curve of coefficients for rest that was obtained with sperm; and the lines for the two oils are almost identical in location. It is thus evident that these peculiar curves are not obtained by a merely accidental set of conditions for either oil.

In these experiments the minimum coefficients for motion were for sperm 0.004, for lard-oil 0.005, and for mineral oil the same as lard. At the same pressures the coefficients for quiescence were 0.15, 0.10, 0.15 for the three oils. Lard-oil permits starting most easily, but it loses its superiority as soon as motion begins.

These relations of value probably differ, however, with every change of speed and temperature as well as of pressure.

141. Temperature modifies Friction to a very important degree, as is seen by examining the tables already given, and especially by studying the following values, which were obtained by heating the bearing by its own friction to a maximum 170° Fahr. (77 C.), well within that liable to produce alterations of the oil, and then noting the friction at successive decreasing temperatures while cooling. It should be remem-

bered that no temperature-readings can be taken as more than approximate.

FRICTION AND TEMPERATURE.

Steel Journals. Lubricant, Sperm Oil. Velocity, 30 *feet per minute.*

Pressure, lbs. per square inch.	Temperature, Fahr.	Coefficient of Friction: f.
200	150°	0.0500
200	140	0.0250
200	130	0.0160
200	120	0.0110
200	110	0.0100
200	100	0.0075
200	95	0.0060
200	90	0.0506
150	110	0.0035
100	110	0.0025
50	110	0.0035
4	110	0.0500
200	90	0.0040
150	90	0.0025
100	90	0.0025
50	90	0.0035
4	90	0.0400

The figures just given would indicate that the sperm-oil used in this instance, and under these conditions, including that of exceptionally low speed, works best at lowest temperatures, and that a heating journal gives rapidly increasing friction and rapidly increasing danger. At usual temperatures—90° to 110° F. (32° to 43° C.)—the best pressure seems to have been from 100 to 150 lbs. on the square inch. The study of the last table is exceedingly interesting and instructive. There are there given coefficients of friction for temperatures from 90° to 150° F., for pressures up to 200 lbs. per square inch, and for velocities of rubbing up to 1200 feet per minute.

It has been seen that at the low speed of 30 feet (9 m.) per minute, the coefficient increases rapidly with increase of temperature, and that at 200 lbs. pressure (14 kgs.), an increase of 50° F. (10° C.) may increase its value to nearly ten times the minimum, the rate of increase rapidly rising as pressures are greater.

It is now found, at speeds of 100 feet (31 m.) per minute, that the friction does not vary between 90° and 150° F. (32 and 66° C.), at pressures below 50 lbs. per square inch (3.5 kgs. per sq. cm.); but that it rises nearly 300 per cent. at a pressure of 200 lbs. (14 kgs.), over 100 per cent. at 150 lbs. (11 kgs.), and 33 per cent. at 100 (7 kgs. per sq. cm.).

At speeds exceeding 100 feet (31 m.) per minute, heating the journal within this range of temperature *decreases* the resistance due to friction, rapidly at first; then, slowly and gradually, a temperature is approached at which increase takes place and progresses at a rapidly accelerating rate. It is seen that this change of law takes place at a temperature of 120° F. (49° C.), and upward; at all higher speeds the decrease continues until temperatures are attained exceeding those usually permitted in machinery and very commonly not far from 150° F. (66° C.), and sometimes up to 180° F. (82° C.), or probably even higher. The Author has found the decrease at 1200 feet (37 m.) per minute to continue up to 175° F. (79° C.), at which the value, at 200 lbs. (14 kgs.) pressure, was, in the cases determined, 0.0050. The limit of decrease is reached under 100 lbs. (7 kgs.) pressure, at 150° F. (66° C.), when running at this high speed.

At 200 lbs. (14 kgs. per sq. cm.) pressure, the *temperature of minimum friction* for conditions here illustrated seems to be, in Fahrenheit degrees, about

$$t = 15\sqrt[3]{V}.$$

On either side this point on the thermometric scale it may be assumed, for a narrow range, to vary, as the temperature departs from that point, directly or inversely, as the case may be, as the temperature. The coefficient of minimum friction is found usually nearly constant over quite a wide range of emperature.

Again, studying in this most instructive of these tables the method of variation with pressure at higher temperatures, we find the effect of change of pressure to be much more marked at the higher temperatures at low speeds; and we note, as when studying the effect of variations of friction with change

of temperature at a standard pressure as affected by variation of speed, that we here find a change of law for the higher speeds.

At a velocity of 1200 feet (37 m.) per minute, the coefficient remains practically uniform with varying pressure at 150° F. (66° C.), while below that temperature the friction coefficient diminishes with increasing pressure. At velocities of rubbing of 250 to 500 feet (75 to 150 m.) per minute the temperature of the constant coefficient is about 100° F. (38° C.); at 100 feet (31 m.) this peculiar condition is seen at about 120° F. (49° C.), when extreme pressures (4 to 200 lbs., 0.28 to 14 kgs.) are compared, but the value is seen to be a little over one half as much at 50 and 150 lbs. (3.5 and 11 kgs.), and to become a minimum—0.0019—at 100 lbs. (7 kgs.) pressure; a similar behavior is noted at the lowest speed observed—30 feet (9 m.)—at about 125° F. (52° C.), and the same fall to a minimum occurs at the intermediate pressure. It would seem that at all times there is a tendency to an acceleration of outflow from the journal, with increase of fluidity due to increasing temperature, which tends to cause an increase of friction, while the effort of capillarity to resist this outflow seems effectively aided by increasing the velocity of rubbing. A balance between these opposite influences is seen to take place at the slowest speed when the pressure is somewhere below 4 lbs. per square inch (0.28 kgs. per sq. cm.); this occurs at a speed of 100 feet (36 m.) per minute at a pressure of 50 lbs. (3.5 kgs.), at 250 feet (77 m.) when the pressure becomes about 150 lbs. (11 kgs.) probably; it happens at a speed of 500 feet (155 m.) at somewhere about the same point; and at 1200 feet (37 m.) per minute the benefit of increased speed is sufficient to produce this balance when the pressure exceeds 200 lbs. per square inch (14 kgs. per sq. cm.).

142. The Law of Variation of Friction with Temperature is evidently not a simple and definite one.

Studying all the results obtained, as above, it becomes evident that every pressure demands a certain degree of viscosity and capillarity in the lubricant to secure at the same time thorough lubrication and minimum friction. The effect of

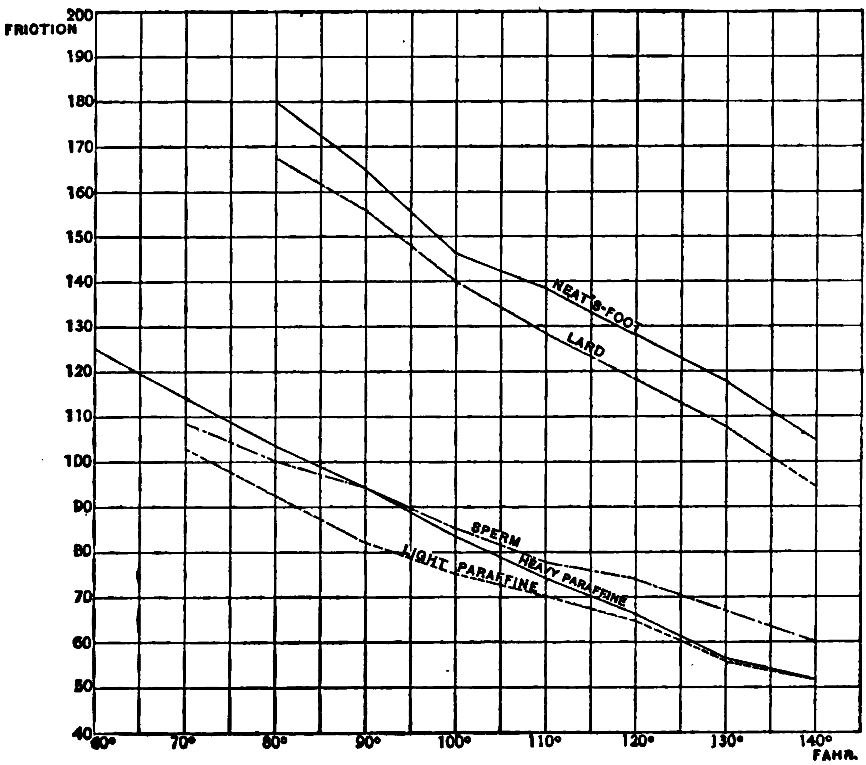

FIG. 53.—FRICTION AND TEMPERATURE.

END OF VOL. I.

variation of temperature is to produce alteration of viscosity, and with low pressures decreased resistance and lessened friction; while with high pressures the effect of increased temperature is to carry the unguent beyond the point at which it can be retained between the surfaces. Thus, at 5 lbs. per square inch (0.35 kgs. per sq. cm.) castor-oil is a very inefficient lubricant at ordinary temperatures; but it becomes equal to the best mineral oils at 200° F. (93° C.). Every oil thus has a maximum value, for each pressure, at a certain definite temperature, and at certain temperatures, different for each, all common oils have the same coefficient. Thus, sperm at about 100° F. (38° C.), a light mineral oil at the same temperature, a heavy mineral oil at 125° F. (52° C.), neat's-foot at 170° F. (77° C.), and lard-oil at 180° F. (82° C.), all have the same coefficient, according to Woodbury, at spindle-pressures. At this light pressure, lard-oil at 130° F. (54° C.) lubricates as well as sperm at 70° F. (21° C.), or the best refined petroleums at 50° F. (10° C.).

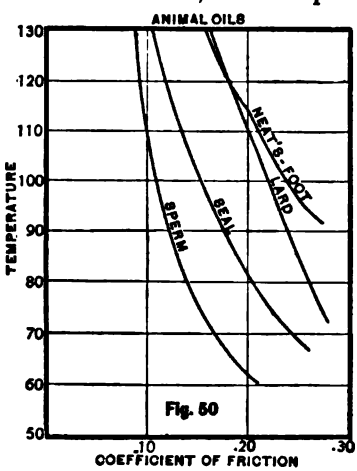

FIG. 54.—FRICTION AND TEMPERATURE.

Fig. 53 exhibits the behavior of mineral, sperm, lard, and neat's-foot oils with varying temperature, as given by Mr. Waite. These curves are very similar to those exhibiting the relation of viscosity and temperature; but, like the others just given, only relate to very low pressures. Under such light loads as are usual in spinning-frames, the resistance decreases very nearly as the temperature rises, within the limits here exhibited. The same facts are exhibited also in Fig. 52, in which the variation of the coefficient, as observed by Woodbury, is shown for several pressures between 1 and 40 lbs. per square inch (0.07 to 3.5 kgs. per sq. cm.).

The method of variation of the friction with temperature is shown in Fig. 54 also.

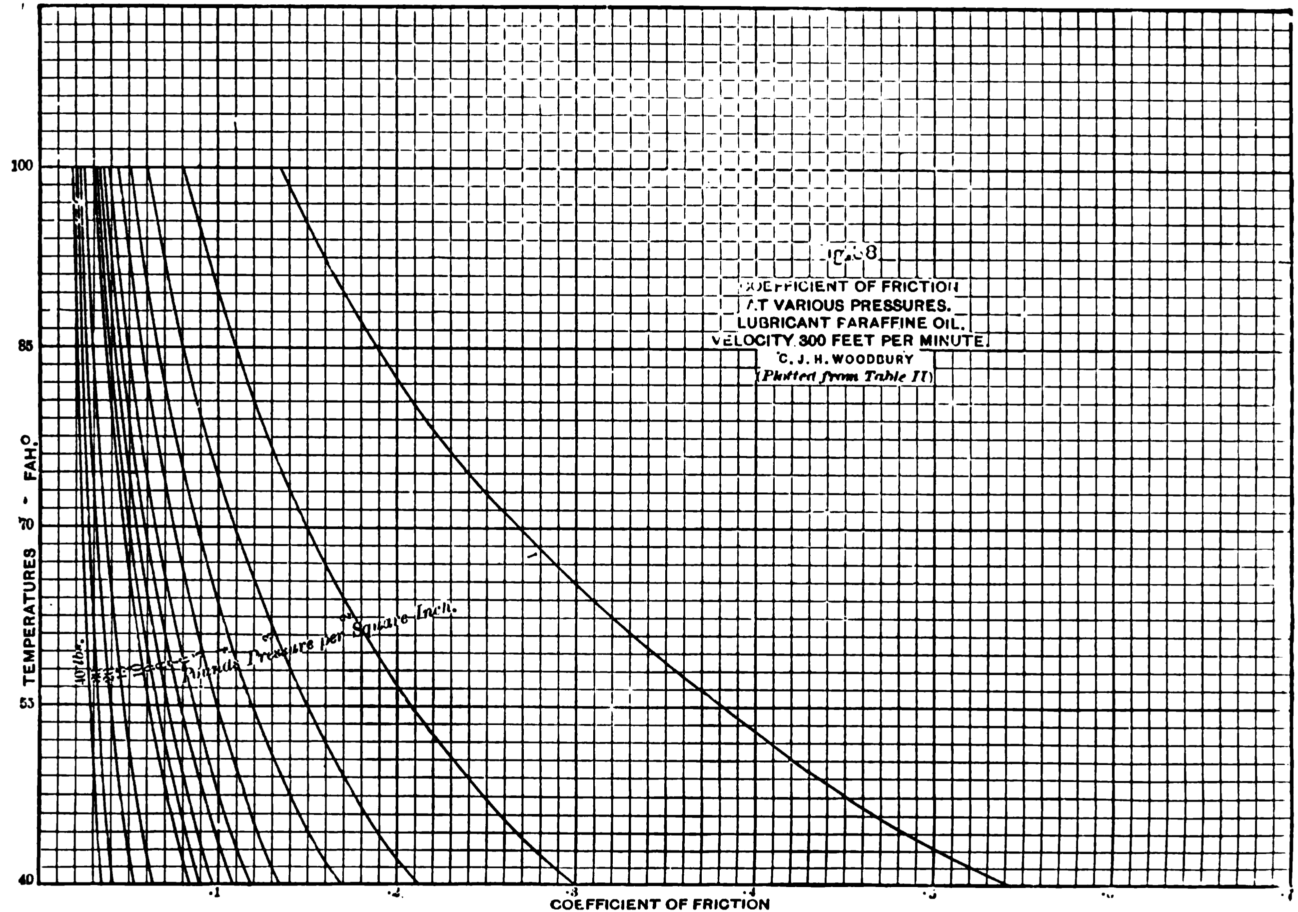

FIG. 55. - FRICTION AND TEMPERATURE

In Fig. 55, this variation of friction with temperature is traced still further, and the general character of the law involved is still better seen than before.

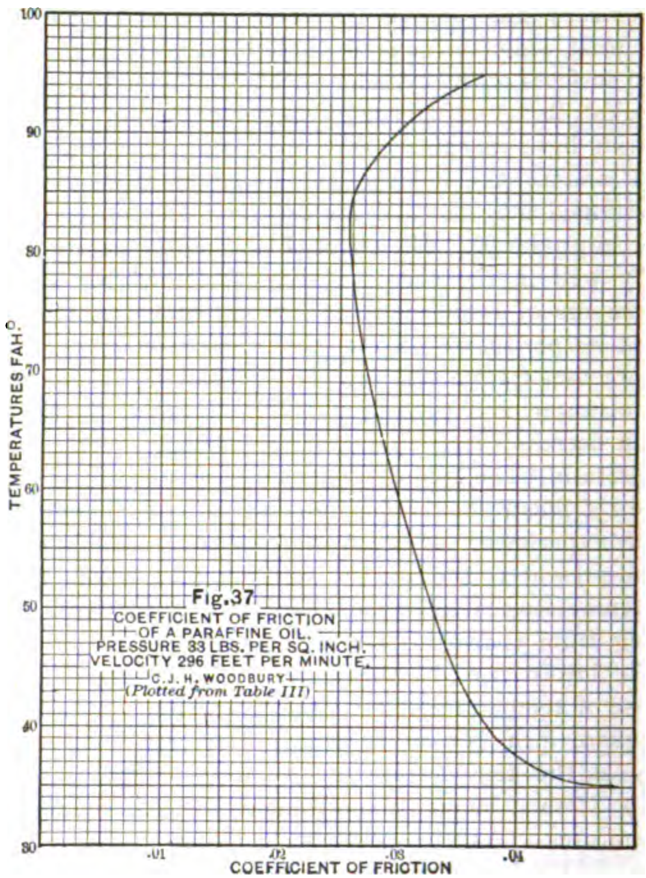

FIG. 56.—FRICTION AND TEMPERATURE.

At low temperatures, the figure shows the large coefficient of friction due to viscosity of the oil, while the rise in friction at higher temperatures indicates a resistance produced by the collision of portions of the disks, and the diagram, Fig. 56, is a graphical representation of the production of a hot bearing.

It is evident that the best lubricant for a bearing in good order is not necessarily the best for a hot journal. The viscous oils and greases, which are comparatively wasteful of power under ordinary conditions, are good unguents for a heating or a chronically hot journal. Castor-oil may be excellent for a hot journal, while kerosene of the lightest grade is best for the chilled surfaces of the cylinder of the compressed-air engine, or the rock-drill. A difference of 50 per cent. may be observed in driving light machinery at temperatures of 50° F. and 75° F. (10° and 24° C.), and the cost in winter of keeping a mill well warmed may be paid for by the reduction in waste of power so produced. The effect of varying temperature is seen equally well in the curves of Fig. 57, which represent the experiments of Hirn, made at low pressures (1.4 lbs. per sq. in.; 0.1 kg. per sq. cm.). The coefficient rapidly falls, as temperature rises from a very low temperature up to the boiling-point of water, and by a peculiar law of variation; from that point it decreases less rapidly, finally varying inversely as the temperature. The record of tests of "cylinder oils" given in article 136 illustrates this phenomenon most strikingly.

The experiments of the Author are shown in Figs. 58 and 59, and present to the eye the method of variation of friction with temperature at more usual pressures, and at various speeds ranging from 30 to 1200 feet per minute (9.1 to 366 metres). At the lowest speeds, the friction rapidly increases with increase of temperature, at all pressures from 50 to 200 lbs. per square inch (3.5 to 14 kgs. per sq. cm.), varying very nearly as the temperature up to 120° or 130° F. (49° to 54° C.); it then increases more nearly as the square of the temperatures. As the pressures and speeds increase, the curves and the law of variation change, until, at 1200 feet per minute (366 m.), sperm-oil exhibits much less friction at high temperatures, and very nearly the same behavior at all pressures. At speeds ranging from 100 to 500 feet per minute (30 to 152 m.), alteration of temperature has little effect, where the oil is fed, as here, by the usual system. With the oil-bath and a flooded journal, as seen later, the effect of temperature is very different, and a very great reduction of friction follows

moderate increase above common temperatures. On the whole, it is evident that, at the speeds and pressures usual in machinery, the resistance decreases as the journals and bearings warm up; and this decrease continues beyond the limit which the engineer considers it best to set to such heating.

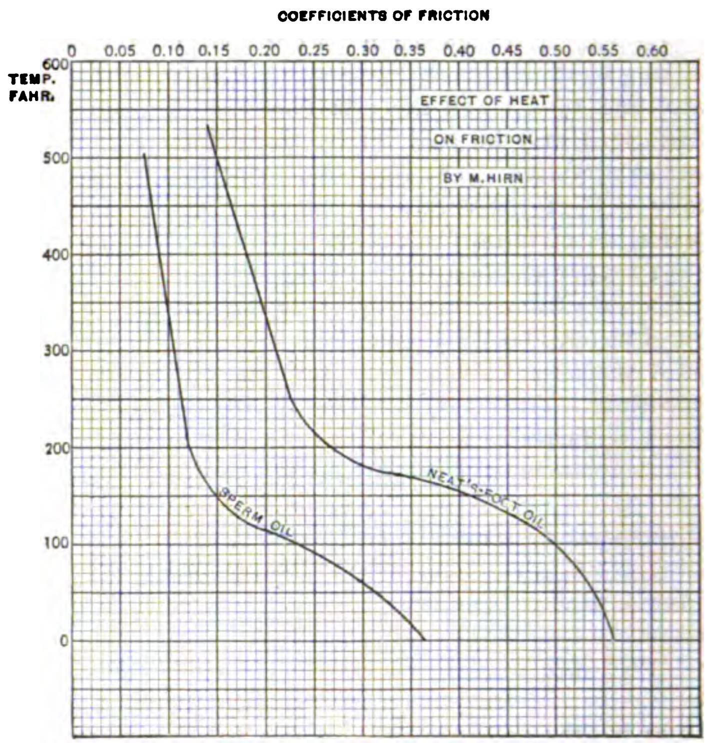

FIG. 57.—TEMPERATURE AND FRICTION.

Fig. 59 shows the same effects when the lubricant is a heavy mineral oil. The same general behavior observed already is here seen. The oil, at the low speeds experimented with, exhibits rapidly increasing friction, with increase of temperature, while at the higher speeds the coefficient rapidly decreases. With this oil the coefficient is constant at some speed lying between 50 and 100 feet (15 and 30 m.) per min-

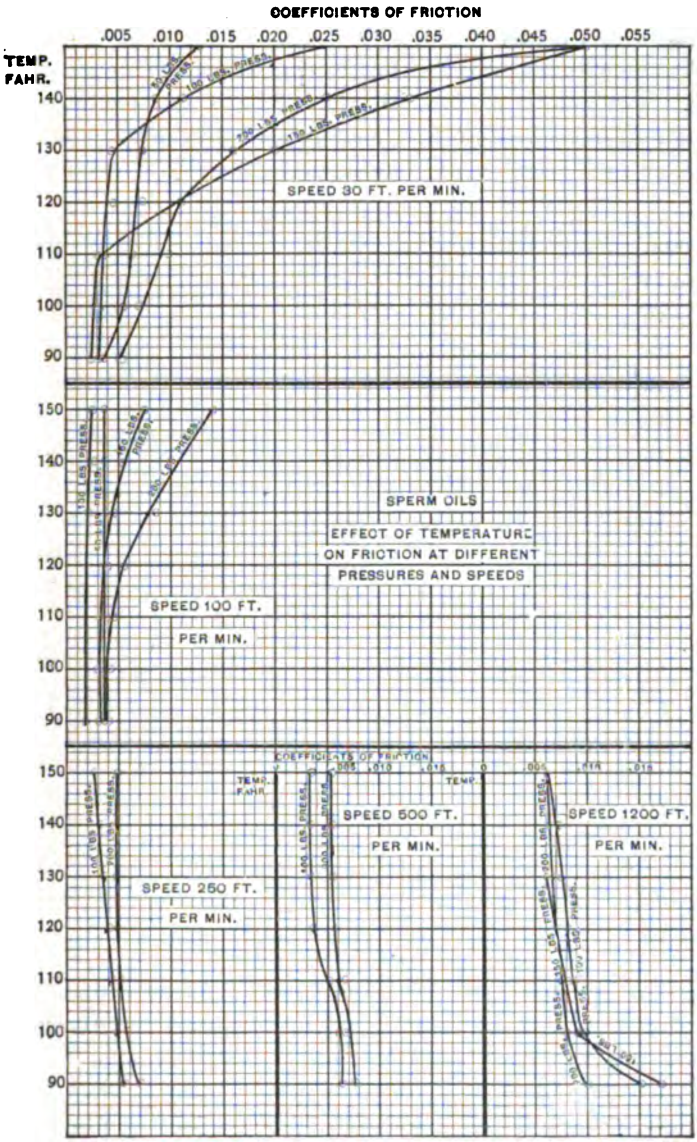

FIG. 58 —TEMPERATURE AND FRICTION.

ute. At 250 feet per minute, change of pressure seems in these experiments to have little effect upon the behavior of the oil in this respect.

As the efficiency of the lubrication improves, as is evident from experiments made with the oil-bath, the coefficient of friction decreases at ordinary temperatures; while the sensitiveness to variation of temperature rapidly increases, the

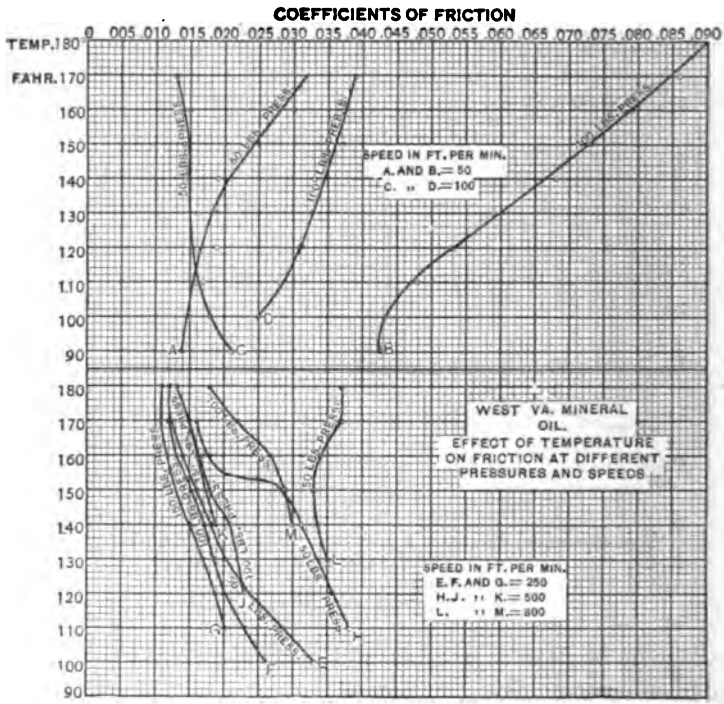

FIG. 59.—TEMPERATURE AND FRICTION.

reverse being noted as effectiveness of lubrication diminishes. But the speed of the journal is an important element, and the higher the velocity, the oil being freely supplied, the more perfect the separation of the metal surfaces by the intervening cushion or layer of oil. Thus it happens that at low speeds, as 30 to 50 feet (9 to 15 m.) per minute, the lubrication is not only inefficient at moderate pressures, but becomes rapidly

more so under higher pressures, and the coefficient increases with rise of temperature toward a limit at which abrasion probably takes place. On the other hand, with oil-bath lubrication, the friction varies very exactly as the square root of the speed.

The work of the Institution of Mechanical Engineers has been reduced and illustrated graphically, as below (Fig. 60),

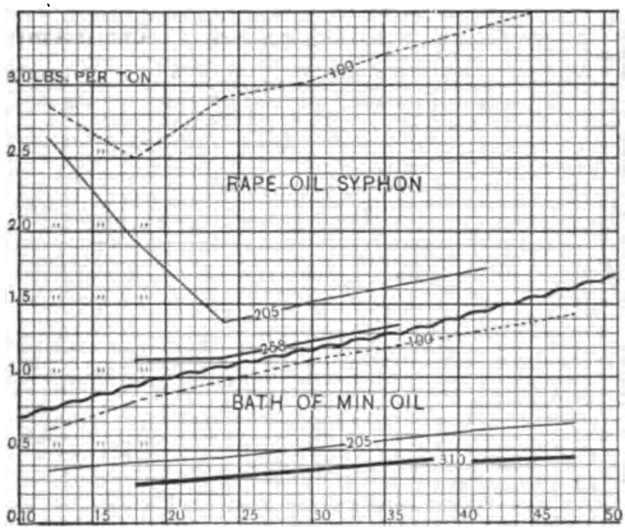

FIG. 60.—TRAIN RESISTANCE.

by Mr. A. M. Wellington, assuming oil-bath lubrication possible in railway service.

The resistance is reduced to pounds per ton, the usual method of statement in railroad work. It is here very well shown that at all usual speeds, with such exceptional lubrication, the resistance increases with speed, rising from 1 lb. per ton at 20, to 1⅝ at 50 miles per hour, when the load is 100 lbs. per square inch. At double this pressure and upward, the same law holds, the resistance falling, however, as the intensity of pressure increases.

The effect of variation of speed in ordinary railway practice

is well shown in the diagram given below (Fig. 61), of results obtained by Mr. Wellington.* The intensity of the pressure per square inch of journal (longitudinal section) is indicated graphically thus:

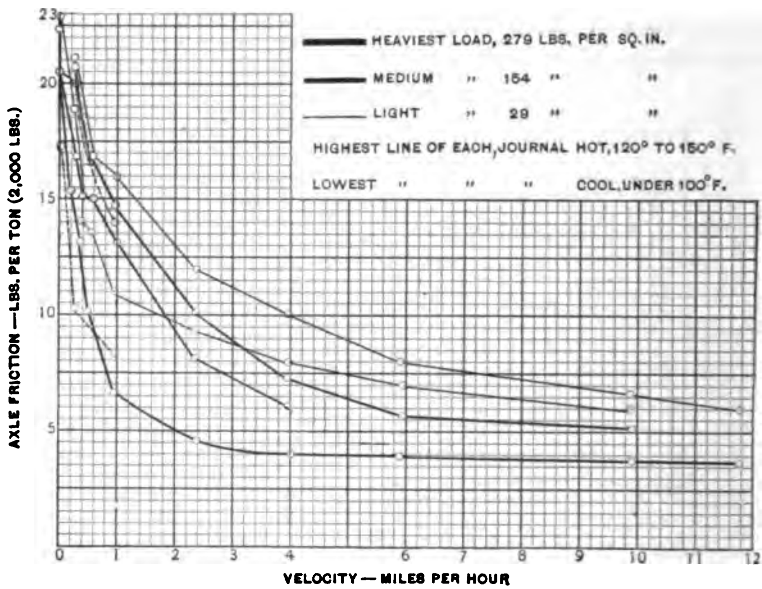

FIG. 61.—RESULTS OF WELLINGTON'S TESTS.

The friction falls with decreasing speed, rapidly at first, then more slowly as the train gradually comes to rest from the speed commonly adopted in freight traffic.

143. Later Researches, corroboratory of the statements of fact and of the deductions presented in the preceding pages, have been made by many investigators. Mr. Beauchamp Tower, some of whose work has been given, conducting experiments, in 1883, for a committee of the British Institution of Mechanical Engineers,† obtained the same general results as had the Author, using a machine of very different construction, with which the pressure was produced by

* Trans. Am. Soc. C. E., 1884.

† Reports of Committee on Friction, 1884.

weighting the journal and the friction determined by the use of a brake somewhat resembling that of Prony, the indications of which were recorded automatically, as had been done by Lux.

In most cases the lubricant was fed to the journal, which was of car-axle size, by the use of a "bath," by means of which the journal could be kept flooded constantly, the friction being thus reduced, as has been elsewhere stated (§ 133), to a small fraction of that met with under more common arrangements. With the more usual system of lubrication, as reported, the results, generally speaking, were uncertain and irregular. The friction depends, in such cases, on the quantity and uniformity of distribution of the oil, and "may be anything between the oil-bath results, and seizing, according to the perfection or imperfection of the lubrication." The oil-bath probably represents the most perfect lubrication possible, and the limit beyond which friction cannot be reduced by lubrication; and the experiments show that with speeds of from 100 to 200 feet per minute, by properly proportioning the bearing surface to the load, it is possible to reduce the coefficient of friction as low as $\frac{1}{1000}$. A coefficient of $\frac{1}{800}$ is easily attainable, and probably is frequently attained, in ordinary engine-bearings in which the direction of the force is rapidly alternating."

With this system the speed of minimum friction was apparently between 100 and 150 feet (30 and 46 m.) per minute.

When using a pad to apply and distribute the oil, the friction showed some approach to variation according to the laws of solid friction. Using the siphon, or ordinary feed-cup, the variation followed very nearly the same law as with the bath, as is also seen by a comparison with the results recorded by the Author. The succeeding tables, given in the report of the committee, represent the more important results. The journal was kept at a temperature of 90° F. (32° C.).

FRICTION OF LUBRICANTS.

Bath of Sperm Oil.

Nominal Load.		Coefficients of Friction, for Speeds as below.							
Kgs. per sq. cm.	Lbs. per sq. in.	100 rev. 105 ft. per min. (32 m.)	150 rev. 157 ft. per min. (48 m.)	200 rev. 209 ft. per min. (64 m.)	250 rev. 262 ft. per min. (79 m.)	300 rev. 314 ft. per min. (95 m.)	350 rev. 366 ft. per min (112 m.)	400 rev. 419 ft. per min (128 m.)	450 rev. 471 ft. per min. (143 m.)
36	520	Seized	.....	....	....	....	.....	....	....
29	415	....	0.0015	0.0017	0.0018	0.0019	0.002	0.0021	0.0021
22	310	....	0.0011	0.0012	0.0014	0.0016	0.0017	0.0018	0.0019
14	205	0.0013	0.0016	0.0018	0.0021	0.0023	0.0024	0.0025	0.0027
10	153	0.0016	0.0019	0.0023	0.0028	0.0030	0.0033	0.0035	0.0037
7	100	0.0025	0.003	0.0038	0.0044	0.0051	0.0057	0.0061	0.0064

Bath of Lard Oil.

Nominal Load.		Coefficients of Friction, for Speeds as below.							
Kgs. per sq. cm.	Lbs. per sq. in.	100 rev. 105 ft. per min. (32 m.)	150 rev. 157 ft. per min. (48 m.)	200 rev. 209 ft. per min. (64 m.)	250 rev. 262 ft. per min. (79 m.)	300 rev. 314 ft. per min. (95 m.)	350 rev. 366 ft. per min. (112 m.)	400 rev. 419 ft. per min. (128 m.)	450 rev. 471 ft. per min. (143 m.)
36	520	....	0.0009	0.001	0.0011	0.0013	0.0015	0.0015	0.0017
29	415	....	0.0012	0.0014	0.0015	0.0016	0.0018	0.0019	0.0021
22	310	....	0.0014	0.0017	0.002	0.0022	0.0025	0.0026	0.0029
14	205	0.0017	0.0020	0.0023	0.0028	0.0031	0.0034	0.0039	0.0042
10	153	0.0022	0.0027	0.0032	0.0037	0.0041	0.005	0.0051	0.0052
7	100	0.0035	0.0042	0.005	0.006	0.0067	0.0076	0.0081	0.009

Bath of Rape Oil.

Nominal Load.		Coefficients of Friction, for Speeds as below.							
Kgs. per sq. cm.	Lbs. per sq. in.	100 rev. 105 ft. per min. (32 m.)	150 rev. 157 ft. per min. (48 m.)	200 rev. 209 ft. per min. (64 m.)	250 rev. 262 ft. per min. (79 m.)	300 rev. 314 ft. per min. (95 m.)	350 rev. 366 ft. per min. (112 m.)	400 rev. 419 ft. per min. (128 m.)	450 rev. 471 ft. per min. (143 m.)
40	573	....	0.00102	0.00108	0.00118	0.00126	0.00132	0.00139	....
36	520	....	0.000955	0.00105	0.00115	0.00125	0.00133	0.00142	0.00148
32	415	....	0.00093	0.00107	0.00119	0.0013	0.00140	0.00149	0.00158
25	363	....	0.00084	0.0096	0.0011	0.00122	0.00134	0.00147	0.00155
18	258	0.00107	0.00139	0.00162	0.00178	0.00195	0.00213	0.00227	0.00243
10	153	0.00162	0.0020	0.00239	0.00267	0.003	0.00334	0.00367	0.00396
7	100	0.00277	0.00357	0.00423	0.00503	0.00576	0.00619	0.00663	0.00714

Bath of Olive Oil.

Nominal Load.		Coefficients of Friction, for Speeds as below.							
Kgs. per sq. cm.	Lbs. per sq. in.	100 rev. 105 ft. per min. (32 m.)	150 rev. 157 ft. per min. (48 m.)	200 rev. 209 ft. per min. (64 m.)	250 rev. 262 ft. per min. (79 m.)	300 rev. 314 ft. per min. (95 m.)	350 rev. 366 ft. per min. (112 m.)	400 rev. 419 ft. per min. (128 m.)	450 rev. 471 ft. per min. (143 m.)
36	520	......	0.0008	0.001	0.0012	0.0013	0.0014	0.0015	0.0017
32	468	....	0.0011	0.0013	0.0014	0.0015	0.0017	0.0018	0.002
29	415	....	0.0012	0.0014	0.0015	0.0017	0.0019	0.0021	0.0024
25	363	....	0.0013	0.0016	0.0017	0.0019	0.002	0.0022	0.0025
22	310	....	0.0015	0.0017	0.0019	0.0021	0.0022	0.0024	0.0027
18	258	0.0014	0.0017	0.002	0.0023	0.0025	0.0026	0.0029	0.0031
14	205	0.0018	0.0021	0.0025	0.0028	0.003	0.0033	0.0036	0.004
10	153	0.0023	0.003	0.0035	0.004	0.0044	0.0047	0.005	0.0057
7	100	0.0036	0.0045	0.0055	0.0063	0.0069	0.0077	0.0082	0.0089

Bath of Mineral Oil.

Nominal Load.		Coefficients of Friction, for Speeds as below.						
Kgs. per sq. cm.	Lbs. per sq. in	100 rev. 105 ft. per min. (32 m.)	150 rev. 157 ft. per min. (48 m.)	200 rev. 209 ft. per min. (64 m.)	250 rev. 262 ft. per min. (79 m.)	300 rev. 314 ft. per min. (95 m.)	350 rev. 366 ft. per min. (112 m.)	400 rev. 419 ft. per min. (128 m.)
44	625	....	0.0013	0.00139	0.00147	0.00157	0.00165	....
36	520	....	0.00123	0.00139	0.0015	0.00161	0.0017	0.00178
29	415	....	0.00123	0.00143	0.0016	0.00176	0.0019	0.002
22	310	....	0.00142	0.0016	0.00184	0.00207	0.00225	0.00241
14	205	0.00178	0.00205	0.00235	0.00269	0.00298	0.00328	0.0035
7	100	0.00334	0.00415	0.00494	0.00557	0.0062	0.00676	0.0073

Bath of Mineral Grease.

Nominal Load.		Coefficients of Friction, for Speeds as below.							
Kgs. per sq. cm.	Lbs. per sq. in.	100 rev. 105 ft. per min. (32 m.)	150 rev. 157 ft. per min. (48 m.)	200 rev. 209 ft. per min. (64 m.)	250 rev. 262 ft. per min. (79 m.)	300 rev. 314 ft. per min. (95 m.)	350 rev. 366 ft. per min. (112 m.)	400 rev. 419 ft. per min. (128 m.)	450 rev. 471 ft. per min. (143 m.)
44	625	......	0.001	0.0012	0.0014	0.0014	0.0016	0.0018	0.002
36	520	......	0.0014	0.0016	0.0018	0.0019	0.002	0.0021	0.0022
29	415	.....	0.0016	0.0019	0.0021	0.0023	0.0025	0.0026	0.0027
22	310	0.002	0.0022	0.0026	0.0029	0.0032	0.0035	0.0038	0.004
14	205	0.0026	0.0034	0.0040	0.0047	0.0053	0.0058	0.0062	0.0066
10	153	0.0028	0.0038	0.0048	0.0057	0.0065	0.0071	0.0077	0.0083
7	100	0.0054	0.0076	0.0094	0.0109	0.0123	0.0133	0.0142	0.0151

The effect of change in the method of oiling is seen in the next two tables, taken in comparison with that above, giving the friction of the same lubricant when applied by the bath:

FRICTION WITH DIFFERENT SYSTEMS OF OILING.

Rape Oil, Fed by Siphon Lubricator.

Nominal Load.		Actual Load.		Coefficients of Friction, for Speeds as below.						
Kgs. per sq. cm.	Lbs. per sq. in.	Kgs. per sq. cm.	Lbs. per sq. in.	100 rev. 105 ft. per min. (32 m.)	150 rev. 157 ft. per min. (48 m.)	200 rev. 209 ft. per min. (64 m.)	250 rev. 262 ft. per min. (79 m.)	300 rev. 314 ft. per min. (95 m.)	350 rev. 366 ft. per min (112 m.)	400 rev. 419 ft. per min. (128 m.)
18	258	22	317	....	0.0056	0.0057	0.0063	0.0068	....	....
14	205	18	252	0.0132	0 0098	0.007	0.0077	0.0082	0.0087	....
7	100	8	123	0 0144	0.0125	0.0146	0.0152	0.0163	0.0171	0.0178

Rape Oil, Pad under Journal.

Nominal Load.		Actual Load.		Temperature.		Coefficients of Friction, for Speeds as below.						
Kgs. per sq. cm.	Lbs. per sq. in.	Kgs. per sq. cm	Lbs. per sq. in.	C.	F.	100 rev. 105 ft. per min. (32 m.)	150 rev. 157 ft. per min. (48 m.)	200 rev. 209 ft. per min. (64 m.)	250 rev. 262 ft. per min. (79 m.)	300 rev. 314 ft. per min. (95 m.)	350 rev. 366 ft. per min. (112 m)	400 rev. 419 ft. per min. (128 m.)
24	328	40	582	32°	90°	....	....	0.0107	0.0102	0.0098	....	....
22	310	38	551	28°	82°	....	0 0099	0.0099	0.0092	0 0099	....	.... ..
21	293	36	520	24°	76°	....	0.0105	0.0105	0.0097	0.0097	....	....
19	275	35	498	25°	77°	....	0.0091	0.0091	0.0095	[illegible]	....	....
18	258	32	458	26°	78°	....	0.0112	0.0095	0.0088	[illegible]	0.0082	0.0083
14	205	25	364	28°	82°	....	0.0105	0.0087	0.0085	0 0073	0.0085	0.01
10	153	19	272	23°	74°	0.0102	0 009	0.0096	0.0102	0.0105	0.0119	0.0125
7	100	12	178	24°	75°	0.0105	0.0099	0.0109	0.0122	0.0133	0.0144	0.0154

The following table illustrates the variation of friction with alteration of temperature through a limited range. The resistance decreases enormously, in this case, with a moderate rise in temperature, becoming but one third the maximum.

FRICTION AND TEMPERATURE.

Bath of Lard Oil. Load, 100 *lbs. per sq. in* (7 *kgs per sq. cm.*)

Temperature.		Coefficients of Friction, for Speeds as below.							
C.	F.	100 rev. 105 ft. per min. (30 m.)	150 rev. 157 ft. per min. (18 m.)	200 rev 209 ft. per min. (61 m.)	250 rev. 262 ft. per min. (79 m.)	300 rev. 314 ft. per min. (95 m.)	350 rev. 366 ft. per min. (113 m.)	400 rev. 419 ft. per min. (128 m.)	450 rev. 471 ft. per min. (143 m.)
49°	120°	0.0024	0.0029	0.0035	0 004	0 0044	0.0047	0.0051	0.0054
43°	110°	0.0026	0.0032	0.0039	0 0044	0.005	0 0055	0.0059	0.0064
38°	100°	0.0029	0.0037	0 0045	0 0051	0.0058	0.0065	0 0071	0.0077
32°	90°	0 0034	0.0043	0.0052	0.006	0.0060	0.0077	0.0085	0.0093
27°	80°	0.004	0.0052	0.0063	0 0073	0.0083	0 0093	0 0102	0.0112
21°	70°	0 0048	0.0065	0.008	0.0092	0.0103	0.0115	0.0124	0 0133
16°	60°	0 0059	0.0084	0.0103	0 0119	0.013	0.014	0.0148	0 0156

The oil-bath used in these experiments by Mr. Tower is not in common use, and cannot always be adopted when desired. The conditions are not, therefore, those of usual practice; but they may be taken as representative of conditions toward which practice should be made to approximate as closely as possible. It is seen that the mixed friction, here met with, approaches more nearly fluid friction than is usual.

Other experiments, reported later by Mr. Tower, exhibited fluid pressures between journal and bearing rising to 625 lbs. per square inch (43 kgs. per sq. cm.), and varying in very nearly the same ratio from the centre-line of the crown "brass," either way to the edge. The journal was found to be thus completely "oil-borne" at speeds as low as 20 revolutions per minute. The coefficient of friction at the latter speed was found to vary nearly inversely as the pressure, exhibiting a minimum at maximum nominal pressure, 443 lbs. per square inch (31 kgs. per sq. cm.), as follows:

COEFFICIENTS OF FRICTION.

Journal 4 inches diameter, 6 inches long. Revolutions per minute, 20; 21 feet per minute (61 m.) speed of rubbing; 90° F. (32° C.), Mineral Oil.

Nominal Load. Lbs. per sq. in.	Kgs. per sq. cm.	f
443	31	0.00132
333	23	0.00168
211	15	0.00247
89	6	0.00440

The experiments just summarized were all made at the high pressures usual in heavy machinery. The accompanying table of coefficients obtained by Woodbury at light pressures, and of which the graphical representation has already been given (§142), are very complete, and are valuable as complementary of the work of other engineers on heavy work. The same general laws are here exhibited, and these values, with those already given, furnish a valuable set of data.

FRICTION OF PARAFFINE OIL.

Velocity of rubbing, 300 feet per minute.

Flash	342° Fahrenheit.
Fire	410° "
Evaporation by exposure to 140° Fahr. for twelve hours.	0.02
Specific gravity	0.888

Pressure in lbs per sq. in.	Temperatures.												
	40°	45°	50°	55°	60°	65°	70°	75°	80°	85°	90°	95°	100°
	Coefficient of Friction.												
1	0.5380	0.4760	0.4260	0.3820	0.3400	0.3020	0.2680	0.2380	0.2120	0.1900	0.1700	0.1500	0.1380
2	0.2990	0.2610	0.2320	0.2080	0.1860	0.1660	0.1500	0.1340	0.1210	0.1090	0.0990	0.0830	0.0800
3	0.2107	0.1853	0.1660	0.1487	0.1333	0.1200	0.1080	0.0980	0.0880	0.0800	0.0733	0.0675	0.0620
4	0.1670	0.1465	0.1310	0.1175	0.1060	0.0960	0.0870	0.0795	0.0725	0.0665	0.0605	0.0540	0.4495
5	0.1400	0.1232	0.1104	0.0966	0.0900	0.0816	0.0740	0.0676	0.0620	0.0592	0.0520	0.0476	0.0416
6	0.1217	0.1067	0.0960	0.0870	0.0787	0.0717	0.0653	0.0597	0.0550	0.0503	0.0463	0.0427	0.0390
7	0.1089	0.0349	0.0847	0.0774	0.0706	0.0643	0.0583	0.0540	0.0497	0.0460	0.0423	0.0388	0.0360
8	0.0978	0.0858	0.0775	0.0705	0.0642	0.0585	0.0540	0.0498	0.0458	0.0423	0.0390	0.0357	0.0335
9	0.0900	0.0791	0.0715	0.0651	0.0593	0.0544	0.0500	0.0460	0.0427	0.0395	0.0367	0.0340	0.0316
10	0.0836	0.0732	0.0666	0.0606	0.0554	0.0508	0.0468	0.0434	0.0402	0.0372	0.0345	0.0324	0.0302
11	0.0782	0.0687	0.0624	0.0571	0.0524	0.0482	0.0445	0.0411	0.0384	0.0356	0.0330	0.0311	0.0289
12	0.0735	0.0648	0.0592	0.0542	0.0498	0.0458	0.0423	0.0390	0.0365	0.0340	0.0315	0.0297	0.0277
13	0.0695	0.0615	0.0561	0.0515	0.0474	0.0437	0.0405	0.0375	0.0349	0.0328	0.0306	0.0285	0.0266
14	0.0663	0.0586	0.0533	0.0491	0.0451	0.0419	0.0389	0.0361	0.0337	0.0317	0.0296	0.0263	0.0259
15	0.0633	0.0561	0.0513	0.0475	0.0435	0.0403	0.0375	0.0349	0.0325	0.0305	0.0280	0.0268	0.0257
16	0.0608	0.0540	0.0494	0.0455	0.0420	0.0390	0.0363	0.0338	0.0316	0.0295	0.0278	0.0261	0.0244
17	0.0582	0.0520	0.0477	0.0441	0.0407	0.0378	0.0353	0.0328	0.0308	0.0289	0.0272	0.0255	0.0240
18	0.0564	0.0504	0.0462	0.0426	0.0396	0.0364	0.0342	0.0321	0.0301	0.0282	0.0264	0.0250	0.0235
19	0.0545	0.0487	0.0448	0.0414	0.0384	0.0358	0.0335	0.0314	0.0295	0.0278	0.0262	0.0245	0.0233
20	0.0528	0.0473	0.0435	0.0403	0.0375	0.0349	0.0327	0.0307	0.0289	0.0273	0.0257	0.0241	0.0227
21	0.0510	0.0460	0.0424	0.0394	0.0364	0.0342	0.0320	0.0302	0.0284	0.0268	0.0252	0.0238	0.0224
22	0.0496	0.0450	0.0414	0.0384	0.0358	0.0334	0.0314	0.0296	0.0280	0.0264	0.0248	0.0234	0.0220
23	0.0483	0.0419	0.0404	0.0374	0.0350	0.0327	0.0308	0.0290	0.0274	0.0258	0.0244	0.0230	0.0216
24	0.0471	0.0436	0.0396	0.0368	0.0342	0.0320	0.0302	0.0285	0.0269	0.0254	0.0241	0.0229	0.0213
25	0.0460	0.0418	0.0386	0.0360	0.0336	0.0314	0.0296	0.0279	0.0265	0.0250	0.0236	0.0226	0.0210
26	0.0448	0.0408	0.0378	0.0352	0.0328	0.0308	0.0290	0.0274	0.0260	0.0246	0.0233	0.0221	0.0208
27	0.0439	0.0400	0.0370	0.0346	0.0322	0.0302	0.0286	0.0270	0.0256	0.0243	0.0230	0.0218	0.0206
28	0.0430	0.0392	0.0364	0.0340	0.0318	0.0298	0.0282	0.0266	0.0252	0.0240	0.0228	0.0216	0.0204
29	0.0421	0.0386	0.0358	0.0334	0.0313	0.0294	0.0277	0.0263	0.0250	0.0237	0.0225	0.0213	0.0201
30	0.0413	0.0378	0.0352	0.0328	0.0307	0.0289	0.0273	0.0259	0.0146	0.0234	0.0222	0.0210	0.0199
31	0.0404	0.0371	0.0347	0.0323	0.0304	0.0284	0.0268	0.0255	0.0243	0.0231	0.0219	0.0208	0.0197
32	0.0397	0.0364	0.0339	0.0318	0.0298	0.0281	0.0265	0.0252	0.0240	0.0228	0.0216	0.0205	0.0195
33	0.0390	0.0358	0.0335	0.0313	0.0294	0.0277	0.0262	0.0249	0.0237	0.0226	0.0214	0.0203	0.0193
34	0.0382	0.0353	0.0330	0.0309	0.0290	0.0274	0.0260	0.0246	0.0235	0.0224	0.0213	0.0202	0.0191
35	0.0376	0.0347	0.0325	0.0304	0.0286	0.0270	0.0256	0.0243	0.0231	0.0220	0.0210	0.0200	0.0190
36	0.0370	0.0342	0.0320	0.0300	0.0283	0.0267	0.0254	0.0244	0.0230	0.0219	0.0208	0.0198	0.0188
37	0.0364	0.0336	0.0315	0.0297	0.0279	0.0264	0.0251	0.0239	0.0228	0.0217	0.0206	0.0196	0.0186
38	0.0358	0.0332	0.0312	0.0293	0.0276	0.0262	0.0248	0.0235	0.0226	0.0215	0.0205	0.0195	0.0185
39	0.0353	0.0328	0.0308	0.0290	0.0274	0.0258	0.0246	0.0234	0.0223	0.0213	0.0203	0.0193	0.0183
40	0.0349	0.0323	0.0303	0.0289	0.0271	0.0256	0.0243	0.0232	0.0221	0.0211	0.0201	0.0191	0.0181

The fact that the coefficient of friction varies greatly with change of pressure is here exhibited with no less certainty. It is also seen that the method of variation varies somewhat with different lubricants, in some cases varying very nearly inversely with the intensity of pressure, and the total frictional resistance remaining nearly constant within wide limits of alteration of pressure. It is here found, as in the experiments

of the Author, that the increase of speed raises the pressure per unit of area attainable, and that the speed giving minimum friction rises with increasing pressure.

The journals in the cases here cited were so arranged that the pressure was unintermitted. It remains to be determined how intermission of pressure modifies the laws affecting friction. It is only known, as yet, that it permits the use of much higher pressures—sometimes double those safely used in the former case.

Some of the most important conclusions which have been deduced from the later experiments described above were anticipated by Mons. G. A. Hirn,* who found by experiment, about 1855, that a lubricant gives least friction after working some time; that friction is diminished by increase of temperature; that, under favorable conditions of lubrication, friction increases in ordinary cases as velocity increases; and that the resistance is proportional to the square root of the product of area and pressure; i.e., the coefficient varies inversely as the square root of the pressure—a conclusion later confirmed by the Author.

144. **Fluid Pressure and Friction** are here controlling conditions. The former evidently in some cases, as seen above, more than mere capillarity, sustains the load, and holds the two surfaces out of contact; the latter produces the observed resistance. The intensity of this pressure was found to be, in experiments already cited, sometimes more than 200 lbs. per square inch (14 kgs. per sq. cm.) when the average load on the journal was one half that amount. In cases such as this, in which no oil-grooves are made in the bearing or in the cap to which the oil-cup is attached, difficulty is often found in securing a free feed of the oil. In nearly all cases the engineer cuts small channels or "oil-grooves" from the oil-hole across or diagonally, or in both directions, to the further portions of the "brass," and thus succeeds in supplying them with oil. Those "reservoir-boxes" in which the oil-bath is incorporated give the best adjustment of fluid-pressure.

* Introduction à la Mécanique Industrielle; Poncelet.

145. **Conclusions.***—**Specified Qualities** may, by the processes here described, be secured by the identification by test of a lubricant possessing such properties. If an unguent is desired for heavy pressures, or an oil for very light work, or for high or low speeds of rubbing under known pressures, the methods of study of the available lubricants which have been described will enable the engineer or the manufacturer to select that which is best suited to the specified purpose. He may go still further, and, by repeated mixing and test gradually improve the mixtures, may finally secure compounds having the best possible qualities for the various proposed applications. The Author has in this manner sometimes produced lubricants for manufacturers which have been found peculiarly well suited for special lines of trade.

Studying the facts here stated, and the data acquired by many hundreds of other experiments, made on one or the other of these last-described machines for testing lubricants, we may recapitulate the facts and figures for ordinary use in machine-design and in estimating losses of power by friction as follows:

(1) The great cause of variation with well-cared-for journals, since they must work at ordinary temperatures, is alteration of pressure and variation in methods of supply; and it is seen that the higher pressures give the lowest percentages of loss of power by friction.

(2) The value of the coefficient is greatly modified by the state of the rubbing surfaces; a single scratch has its effect in wasting power. A good journal usually has its surface as smooth and as absolutely uniform as a mirror. Every well-kept journal acquires such a surface.

(3) For general purposes and for heavy work, as in the experiments of the Author, and at considerable speeds, the value of the coefficient varies nearly inversely as the square root of the pressure, for pressures ranging from 50 to 500 lbs. per square inch.

(4) The coefficient for rest or starting may similarly be

* See Trans. Am. Inst. Mining Engineers, 1878; Journal Franklin Institute, November, 1878.

taken to vary nearly as the cube root of the pressure. For closer estimates and other conditions, the tables just given can be referred to directly.

(5) The coefficient for the instant of coming to rest, under the special conditions here referred to, is nearly constant, and may be taken at 0.03.

(6) The resistance due to friction varies with velocity, decreasing with increasing velocity rapidly at very low speeds, as from 1 to 10 feet per second, and slowly as higher speeds are reached, until the law changes and increase at ordinary temperatures takes place, and at a low rate throughout the whole range of usual velocities of rubbing met with in machinery.

Its amount and the law vary with method of lubrication, however. With oil-bath lubrication the value of f usually varies more nearly as the square root of the velocity.

(7) With pressure and velocity varying, we may take the coefficient as varying as the fifth root of the velocity, divided by the square root of the pressure for such work as is represented by the experiments of the Author.

(8) The effect of heating journals under conditions here illustrated is, to *increase* the friction above 90° or 100° F., at a speed as low as 30 to 100 feet per minute, while at higher speeds and low pressures the opposite effect is produced, and the coefficient often *decreases* more nearly as the square root of the rise of temperature.

(9) The temperature of minimum friction, under the conditions of the experiments here referred to, varies nearly as the cube root of the velocity, for a pressure of about 200 lbs. per square inch.

(10) The endurance of any lubricant should be determined by actual wear upon a good journal under the pressures and velocities proposed for its use.

The economy with which it can be used will be dependent upon its natural method and rate of flow, and upon its capillary qualities, as well as upon its intrinsic wearing power and the method adopted in feeding it. Greases, therefore, are usually more economical in cost than oils, even if having less wearing capacity.

(11) The only method of learning the true value of a lubricant and its applicability in the arts is to place it under test, determining its friction-reducing power, and its other valuable qualities, not only at a standard pressure and velocity, and at ordinary temperatures, but measuring its friction and endurance as affected by changing temperatures, speeds, pressures, and methods of application, throughout the whole range of usual practice.

(12) The true value of an oil to the consumer is not proportional simply to its friction reducing power and endurance, under the conditions of his work; but its value to him is measured by the difference in value of power expended, when using the different lubricants, less the difference in total cost of oil or grease used; but for commercial purposes, no better method of grading prices seems practicable than that which makes their market value proportional to their endurance, divided by their coefficients of friction.

The consumer will usually find it economical to use that lubricant which is shown to be the best for his special case, with little regard to price, and often finds real economy in using the better material, gaining sufficient to repay excess in the total cost very many times over.

(13) To secure maximum economy, the journal should be subjected to a pressure the limit of which is determinable by either Rankine's or Thurston's formula (Art. 127); the most efficient materials should be chosen for the rubbing surfaces; they should be reduced to the most perfect state of smoothness and perfection in form and fit; a lubricant should be chosen which is best adapted for use under the precise conditions assumed; the lubricant should be supplied precisely as needed, and by a method perfectly adapted to the special unguent chosen. The real problem is often not what oil shall be used, but how to secure most effective lubrication.

(14) The semi-fluid lubricants, when equally good reducers of friction, are usually the most economical for heating journals, in consequence of their peculiar self-regulating flow, as the rubbing parts warm or cool while working. They are usually too viscous for economical use in ordinary work.

CHAPTER VIII.

THE FINANCE OF LOST WORK AND THE VALUATION OF LUBRICANTS.

146. The Conditions affecting Values, both of the lost work produced by friction and of the unguent used in reducing its amount, have been already stated (Art. 51, Chap. III.) to involve other and far more important considerations than the market-price of the lubricant. The principles involved were stated by the author in an earlier work;* the treatment to be here given is a more complete development of the subject. Demand usually, if sufficient time is allowed for its operation, brings prices into a correct relative order, but not necessarily into a true proportion of values for any one specific application. It is generally the fact that "the best is the cheapest" to the consumer, and this rule is probably almost always applicable in the purchase and use of lubricants. It is frequently the fact that the consumer can better afford to use the highest-priced article than to take those of lower value as a gift.

A very roughly approximate value by which to compare the oils can be sometimes based on the assumption that they will have a money-value proportionate to their durability and to the inverse ratio of the value of the coefficient of friction. Thus: Suppose two oils to run, one 10 minutes and the other 5, under a pressure of 100 lbs. per square inch, and both at the same speed, and suppose them to give on test for friction the coefficients 0.10 and 0.06 respectively.

Their relative values might be taken at $\frac{10}{10} = 1$ and $\frac{5}{6} = 0.833$. If the first is worth one dollar the second should be worth $83\frac{1}{3}$ cents.

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* Friction and Lubrication. R. H. Thurston, New York, Railroad Gazette Pub. Co., 1879.

In many cases, however, about the same quantity would be applied by the oiler, whatever oil might be used, and their values to the consumer would be taken in the inverse proportion of the values of their coefficients of friction, i.e., as, in the above case, 6 is to 10, thus making the value of the second $1.66⅔, and showing that it would be better to use the latter at anything less than this price than the first at one dollar.

Engineers have been accustomed to use these methods of comparison in reporting upon the values of lubricants simply because they are generally considered to be correct by dealers and users, and because there has been no better method suggested of assigning an approximate figure for market price.

The real difference in values of any lubricants, to any user, may, nevertheless, be determined in any given case when the cost of power is exactly known, and when the quantity of the several unguents required to do the same work has been found, and their several coefficients of friction given. The difference in actual value to the user, where any two unguents are compared, is measured by the difference in the costs of power and other expenses expended in driving the machinery when lubricated first with the one and then with the other of the two materials. As power is usually much more expensive when developed in small, than when demanded in large, amounts, the economy to be secured by adopting a good lubricant is the greater as the magnitude of the work is less. In large mills, and wherever work is done on a very large scale, the cost per horse-power and per annum may be taken roughly at about $50 a year, while for small powers this figure is doubled or even trebled and quadrupled.

Every reduction of power to the extent of one horse-power, by the introduction of an improved material or system of lubrication, thus effects a saving of $50 to $100 a year; the difference between this amount and the extra cost of the new kind of lubricant represents the annual profit made by the change. Should it happen, as is sometimes the fact, that the better unguent is also the cheaper, an additional profit is made which is measured by that saving in cost.

In an ordinary small mill or in a machine-shop in which 100

horse-power is used, a change in lubricant will often effect an average saving of 5 horse-power and a consequent economy of, probably, $500 a year. The total amount of oil used in such a case might considerably exceed 100 gallons.

The consumer could in such a case better afford to pay $5, or perhaps even more, per gallon for the good oil than accept the less valuable lubricant as a gift.

In mills filled with light machinery, where the mean value of the coefficient of friction is greater, and where a larger proportion of the total power expended is used in overcoming the friction of lubricated parts, a saving of 15 or 20 per cent. has been made by the substitution of a good oil for a worse, i.e., a gain of 75 to 100 horse power on 500, and of $3000 to $5000 per annum in power alone. In a case reported by Mr. Comly,* a reduction of cost of oil on a single engine from 3.53 to 0.78 cents per hour was effected by the use of a slowly-flowing grease instead of a freely-flowing oil. The cost of lubrication of shafting was similarly reduced 44 per cent., but the loss by increased friction was not noted. An instance is reported by Mr. Woodbury† in which a gain of power of 33 per cent. was effected by change of grease for a light oil, the loss in cost of lubricant becoming comparatively unimportant; in still another instance the production of a mill was thus increased 5 per cent., while also greatly reducing the lost work of friction.

This subject is of such importance, and has as yet received so little attention, that it has been considered advisable to devote a chapter to its development.

The differences in value of good oils, and the enormous wastes of power, and of other costs, with unguents of poor quality, are easily exhibited. Assuming the cost of a good oil at $1 per horse-power per annum, in any case, a variation of one per cent. in the coefficient of friction produced by a change of oil will produce a gain or loss of from 50 to 100 per cent. of the total cost of oil used in the shop or mill, and of other costs of power accordingly as the mean coefficient is high, as in cotton and other mills filled with light mechanism,

* Trans. Am. Soc. M. E., 1884. † Ibid.

or low as in the locomotive engine and other heavy machinery. The use of good instead of bad, or of an oil with low "cold-test" in winter instead of one easily stiffened by low temperature, may enable an engine to haul two or three additional cars in a train, or a mill to be driven easily and economically, where otherwise it could not be driven, if at all, by an engine of proper proportions except very wastefully.

The use of a poor quality of cylinder-oil will sometimes cause losses by increased friction of engine, and even on locomotives by breakage of rods and rock-shafts, sufficient to compensate many times over the gain in money cost of oil. Under heavy pressures, also, the cost of wear and tear of journals and bearings may become a serious item.

All lubricants should be purchased with careful regard to their *value*, rather than by reference mainly to their *price*. Their value is determined principally by their friction-reducing power, and their reduction of wear of rubbing parts. Unguents of low grade cause losses, direct and indirect, which are out of all proportion to their low cost, and may invariably be expected to produce such losses by waste of power, by injury to journals and bearings, and by destruction of valuable machinery, to say nothing of the dangers of fire which often accompany their introduction, that the user can generally better afford to pay many times their value for the privilege of declining to use them, than to submit to the enormous losses sure to follow their application to his machinery. In every case the lubricant should be carefully selected for the special use intended.

147. The Defects in the Usual Methods of valuation of lost work and of lubricants are readily seen to arise from the fact that they include simply a comparison of the market-price of available kinds and qualities with their endurance and friction-reducing power. It is usually assumed that, of two oils having endurance and friction-coefficients in the inverse ratio of their prices, the purchaser may take either with practically equally good financial result. No comparison is usually made of the relative costs of wasted power and of total expense for oil. This system is obviously entirely wrong, as is every method which does not take into account every item of profit

and loss variable with change in quality and quantity of lubricant, and which does not make up an account including all these items. The real question is not whether the difference in price of any two oils is justified by the difference in their intrinsic qualities, but whether the profit or loss to be made by the substitution of one for the other is compensated by the total loss or gain in expense.

148. **An Exact Method** of valuation of lost work and of lubricants must include a determination of the intrinsic qualities of the latter, their influence upon the magnitude of the former, and of the money-value of every item of gain and loss in the purchase of the lubricants, in the variation of the quantity of power used, and in all incidental expenses, such as wear and repairs, taxes, insurance, rents, availability of the property, and many other items that may be usually determined in any given case. An expression must be obtained for the total of all these costs of wasted power and of lubricant for the actual and for the proposed case, and a comparison of the amounts so determined will indicate the magnitude of the gain or loss to be produced by the proposed change.

149. **The Theory of the Finance of Lost Work** includes a comparison of economy in the use of various lubricants, which is evidently not that of the relative cost of operation with and without lubricants, but of the relative total costs of working with two or more available unguents. The costs include the expense of the lubricant and of repairs, and the value of the work wasted by friction in the several cases.

If the cost of the lubricant per unit of quantity is k, and if the quantity used in the assumed time be q, the cost of the lubricant is kq. If the amount of work lost by friction in the given time be U, and if its total cost be k' per unit of work, and for the assumed time, the expense chargeable to lost work is $k'U$; while the total expense due to friction of the apparatus is, neglecting other expenses as unimportant,

$$K = kq + k'U. \quad \ldots \ldots \quad (1)$$

But the work is

$$U = afPS = afPVt, \quad \ldots \ldots \quad (2)$$

the product of the coefficient of friction, f, the total load, P, the mean velocity of rubbing, V, the time, t, and a constant, a, dependent upon the relations assumed for space and time; hence,

$$K = kq + k'afPS. \quad . \quad . \quad . \quad . \quad . \quad (3)$$

For any given cases taken for comparison, the only variables in the second member of the above equation are q and f, and, making $ak'PS = b$,

$$K = kq + bf; \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad (4)$$

in which b is determinable for each case of comparison. That lubricant which gives the least value of K is best. The true value of a proposed oil will vary as

$$k = \frac{K - bf}{q}. \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad (5)$$

The above equations show that the value of the lubricant is inversely as the quantity required, and, when the cost of unguent is small in comparison with the value of the lost work or wasted power, its commercial value, which varies with the decrease effected in K, is directly as some function of its lubricating power, i.e., nearly as the reciprocal of the coefficient of friction. If the cost of oil is large, the comparison becomes one of the expense for lubricants.

Two oils being compared, the costs of lost work are, respectively,

$$K_1 = k_1q_1 + bf_1; \qquad K_2 = k_2q_2 + bf_2;$$

and the saving effected by the substitution of a better lubricant is

$$K_1 - K_2 = k_1q_1 - k_2q_2 + b(f_1 - f_2). \quad . \quad . \quad . \quad (6)$$

When $K_1 = K_2$, (6) becomes zero, and since

$$k_2q_2 - k_1q_1 = b(f_1 - f_2),$$

the change is a matter of indifference; if $K_1 - K_2$ is greater, the change is advisable, otherwise it is not; and where $K_1 = K_2$, the gain by lower cost of oil is just compensated by increased loss of power. Thus the equation

$$k_2 q_2 - k_1 q_1 = b\,(f_1 - f_2),$$

$$k_x = k_2 = \frac{k_1 q_1 + b\,(f_1 - f_2)}{q_2}, \quad . \quad . \quad . \quad (7)$$

is the criterion determining advisability of making a change of lubricant. A higher cost for the proposed oil than k_x would be uneconomical.

It is very often the fact that the quantity of the oil used has little connection with the behavior of the journal upon which it is used, and q_1 may be taken equal to q_2, when the expression becomes the condition of economy, and the criterion is given by

$$k_x = k_2 = \frac{b}{q_1}\,(f_1 - f_2) + k_1. \quad . \quad . \quad . \quad . \quad (8)$$

Where the effects of using different quantities of the same oil are compared, $k_1 = k_2$, and the criterion is

$$q_2 = \frac{b}{k_1}\,(f_1 - f_2) + q_1; \quad . \quad . \quad . \quad . \quad . \quad (9)$$

the use of any quantity less than q_2 is an advantage. As the friction of lubricated surfaces is sometimes enormously affected by the freedom of supply of the unguent, the consideration of this case is very important. The lower the price of the lubricant, and the higher the value of the power, the more freely may the oil be supplied.

In all such cases, therefore, we have the cost of wasted power a function of q_1, and when, as is always the fact in practice, the law connecting the variation of K with the variation of q can be ascertained. exactly or approximately, by experiment, and can be expressed by an algebraic equation, the most

economical rate of supply, i.e., the best value of q_1, may be determined by making

$$\frac{dK}{dq} = 0$$

for a minimum.*

When the relative durability and the coefficients of friction are known, as determined by experiments made under the exact conditions of intended use, it becomes easy to determine their relative values. Taking that actually in use as the standard, if the proposed lubricant be found to have e times the endurance of the standard, the quantity used will be $q_2 = \frac{q_1}{e}$. If the second oil also have a coefficient of friction h times as great as the first, the work of friction will be correspondingly decreased or increased, and the cost of that work will be bhf_1. The total costs thus become

$$K_1 = k_1 q_1 + bf_1; \quad . \quad . \quad . \quad . \quad . \quad . \quad (10)$$

$$K_2 = k_2 \frac{q_1}{e} + bhf_1; \quad . \quad . \quad . \quad . \quad . \quad (11)$$

and the criterion of economy is given by making $K_1 = K_2$, and

$$k_a = k_2 = \frac{e}{q_1} [k_1 q_1 + bf_1 (1 - h)]. \quad . \quad . \quad (12)$$

A higher cost causes loss, a lower is a gain; this value of k being that which the buyer can pay for the lubricant in place, on the journal, without losing by the change.

It is obvious that b may be expressed in any units of cost that may be convenient, as on railroads, in repairs, fuel, or other material expended per train-mile. Thus on railroads the expenses of hauling trains are measured by the costs of oil, repairs, and of power per train-mile, and

$$K = kq + df, \quad . \quad . \quad . \quad . \quad . \quad . \quad (13)$$

* See Friction and Lubrication; also, Encyclopedia Britannica, art. "Lubricants."

in which q is the quantity of oil used and df is the cost of power and attendant expenses per train-mile. This makes the criterion

$$k_1q_1 - k_2q_2 = d(f_1 - f_2);$$

$$k_m = k_2 = \frac{k_1q_1 + d(f_1 - f_2)}{q_2}. \quad . \quad . \quad (14$$

Where, as may often occur, the reduction of friction is accompanied by increased expenses on account of wear of journals and bearings, a third term must be introduced and the variation of the total thus obtained noted. For ordinary pressures, in well-designed mechanism, the last item may probably be neglected; but in some cases, as in transportation on railways, it may become, and probably often is, a very serious item of expense, and must be taken into account.

150. Data required in Applying the Theory, although usually obtainable with satisfactory exactness in any given case, are not sufficiently uniform to permit their statement in figures for general use.

The total expense chargeable to lost work in machinery consists of the following items:

(1) Cost of power produced, only to be wasted, including all items of cost in the motive-power department.

(2) Expense incurred by "wear and tear" of the driven machinery and its repair and replacement.

(3) Indirect, casual, and remote money-losses due to inefficiency caused by friction and by wear.

(4) Cost of lubricants and of their application.

The first item includes all running expenses of the motor, including fuel and supplies, interest on invested capital, wages, insurance, and taxes on the engine, boilers, and buildings covering them. The second, which is a large item, includes the replacement of worn bearings and journals, and parts included in their depreciation, sometimes the latter involving finally the whole machine. In fact this is the usual limit of the life of the machine. The third item cannot be calculated, since it includes accidents, but it may usually be covered, like

other casualties, by a system of insurance. The fourth item is the least important of all. It includes the purchase of the lubricant, its transportation, and the expense of its application and removal and of keeping the bearings clean. Although the smallest of these expenses, this is most obvious to the consumer, and is wrongly allowed to determine, usually, the selection of the unguent. A change of lubricant usually effects enormous changes in the magnitudes of the first three items, and comparatively insignificant alterations of cost in the last. As the total resistance is composed partly of friction of fluids, and partly of that of solids, some lubricants are found to give reduced resistance, while nevertheless increasing wear inordinately. In such cases, the lubricant is found to have too small viscosity, and the decreased fluid resistance, although not compensated by increase of solid friction, is more than counterbalanced in the expense account by cost of increased wear.

151. **The Units of Measurement** to be adopted in the commercial theory of lost work will be determined by circumstances. As a rule, the cost of power is measured in dollars or cents per horse-power, or per foot-pound, per hour of working time, which is usually about three thousand hours per annum. The usual charge for the horse-power in New York City, for example, in small amounts, is $100 per annum, equivalent to $0.033 per hour. The cost of wear and tear and of depreciation is very variable, but can be best estimated as a percentage of the value of the machinery; 2½ per cent. for renewals and something more for minor repairs is a common figure. All taxes and insurances are reckoned by a similar method. The cost of lubricants may be reckoned from the quantity used per hour.

All expenses being thus reduced to one measure—money-cost—it becomes easy to solve any problem of this kind arising in practice when the requisite data are obtainable.

The costs are thus made to appear finally as two items—the one the cost of the lubricant, and the other that of the wasted power—which are regarded as independent variables, although evidently dependent according to some law which may possibly be sometimes easily expressed. The data required are often exceedingly difficult of determination, and

approximate results only can be reached. This is especially true of cost of wear and repairs.

152. The Values of Quantities entering the preceding theory are often ascertainable: they are mainly costs of power, of oils, and of depreciation. The cost of power will vary according to amount, efficiency of engine, costs of wages, fuel, and minor items, from $40 per annum, or $0.013 per hour, to $200 per year, or $0.07 per hour, nearly: the higher figures being for very small, and the lower costs for large and economical condensing engines, with cheap fuel and labor. The mean may be assumed as $60, or $0.02 per hour, for good non-condensing, stationary engines of 100 to 200 horse-power.

This annual expense is divided, in some cases noted by the Author, thus:

	Total.	Coal and Oil.	Wages.	Minor Costs.
Small engines	$200	$50	$100	$50
Medium "	60	25	25	10
Large "	40	20	10	10

In marine work, the cost of fuel often becomes a larger percentage of the total; perhaps 60 to 80 per cent. may be considered a common allowance.

The power demanded for overcoming friction of engine and shafting of mills may be taken at from 0.20 of the total on heavy work, to 0.30 on light, the total power ranging from 10 to 20 horse-power, averaging 15, per 1000 spindles and "preparation."

The cost of oils in the market has no direct relation to their values as lubricants, and is not infrequently in the inverse order, the best costing least, and the most expensive having a comparatively low position as unguents for the specific purpose considered. Taking them as they come, however, the following may, for purposes of illustration, be assumed to be fair relative values:

Sperm-oil, per gallon	$1 10
Neat's foot oil, per gallon	1 00
Lard oil, " "	0 70
Tallow-oil, " "	0 70
Olive-oil, " "	0 90

Cotton-seed oil, per gallon	0	50
Greases, per pound	0	25
Mineral oil, heavy and fine	0	80
" " fair	0	50
" " light	0	40
" " spindle, light	0	30
" " natural W. Va	0	25
" " kerosene	0	10

The quantity used will vary greatly with its use and the method of application. Cotton-mills use from 10 to 30 gallons per 10,000 lbs. of cloth made, or about 10 gallons per annum per horse-power, at a cost averaging \$0.70 to \$1.00 per gallon. A mill of 60,000 spindles, making 3,000,000 lbs. of cloth per year, and demanding 1200 horse-power, uses about \$2000 worth of oil. The cost of replacement of wearing parts is small. Railway-engines use 0.005 to 0.01 gallon per "train-mile," and 40 to 60 lbs. of coal. Cylinder oils are used in the proportion of from 200 to 600 miles run per gallon.

The ordinary passenger locomotive on New England railroads averages an expenditure of between 60 and 70 lbs. of coal per mile, at a cost of not far from 15 cents; while an expense of one half cent per mile for oil and tallow is considered a good showing. A run of 30 miles per ton of coal and of 100 miles per gallon of oil is not an unusual figure on Western roads. The cost of fuel is often about one third the total cost per mile; that of oil about two or three per cent of the total. Two or three times as much oil is used under a passenger car as under a freight car. The cost of repairs is enormously variable. It has been found in some cases of good practice that a pound of bearing and a pound of journal are worn away by, respectively, twenty-five thousand and seventy-five thousand miles of travel. But the cost of this form of depreciation alone is enormously greater than the mere cost of material per pound. Using a black oil, the cost of wear has been found five times that of the lubricant and twice that of power.

A large machine-shop is reported to have used one thousand tons of coal per annum for all purposes, including heating, to demand 120 horse-power from its engines, and to use 450

gallons of oil, the cost being \$6500 for coal and \$250 for oil. Another moderately large shop uses but 60 gallons of oil per year, or about 0.02 gallons per hour of working time. The cost of wear should be insignificant.

153. **Illustrations of Application** may be taken as below:

Calling the total value of the horse-power \$100 per annum, or \$0.03 per hour, the value of b will be found as a function of $k'afPS$. The value of k' will be

$$k' = \frac{.03}{1,980,000},$$

if a is taken as unity, i.e., one hour, and

$$b = 0.000,000,015\, fPS.$$

Assume $PS = 4,000,000,000$ a fair figure for an iron-working establishment wasting 100 horse-power in friction. Then $b = \$60 = 0.6$ H. P.; and if in equation (4) $f = 0.05$, $k_1 = \$0.50$, and $q_1 = 0.02$ gallon per hour,

$$K_1 = k_1q_1 + bf_1 = 0.01 + 3.00 = \$3.01.$$

Assume $k_2 = \$0.25$; $q_2 = 0.03$; $f = 0.06$; then

$$K_2 = k_2q_2 + bf_2 = 0.0075 + 3.60 = \$3.60\tfrac{3}{4};$$

$$K_1 - K_2 = -\$0.60 \text{ nearly.}$$

The cost of lost power is increased 20 per cent, and \$0.60 per hour is lost by a saving of one quarter of a cent per hour in cost of lubricant by the substitution of an oil giving a coefficient of 6 per cent., and demanding one half more oil for a lubricant giving a mean coefficient of 5 per cent. The saving in cost of oil is insignificant; the loss in cost of power is comparatively enormous; although the difference in the coefficient is but one per cent.

If by freer supply of the cheaper oil, as by the oil-bath, the

value of f_1 can be reduced, as is not unlikely, to $f_1 = 0.02$, if $q_1 = 0.40$ and $k = 0.25$, we get

$$K'_2 = 0.10 + 1.20 = \$1.30;$$

$$K_2 - K'_2 = \$2.30; \; k_2q_2 - k'_2q'_2 = \$0.0925;$$

and the expenditure of nine cents per hour for additional oil produces per hour a gain of $2.30, i.e., a profit of about 2500 per cent.

If one oil gives a mean coefficient of friction, $f_1 = 0.05$ and another $f_2 = 0.06$, using 0.02 gallon per hour of each, the real value of the latter becomes (Eq. 7)

$$k_2 = \frac{0.01 + 60\,(0.05 - 0.06)}{0.20} = -\,\$2.95,$$

and the proprietor will do well to pay $3.05 per gallon for the privilege of declining its use; since, if it is used, he loses that amount on every gallon.

If a low-grade oil be in use at $k_2 = \$0.25$ per gallon, giving $f_2 = 0.06$ when using $q_2 = 0.2$ gallon per hour, it will pay to substitute the higher quality at any cost not exceeding, per gallon,

$$k_1 = \frac{0.05 + 60\,(0.06 - 0.05)}{0.20} = \$3.25,$$

which exceeds several times the cost of the most valuable oils used for lubrication.

In fact, as is evident, the importance of reduction of the cost of unguent is usually absolutely insignificant in comparison with that of securing the best possible lubrication. The fact is also here made evident, that no system of determination of the relative value of lubricants can give more definite results than that of applying the steam-engine "indicator" to the driving-engine, and using the oils to be compared one after another, and long enough to eliminate the effect of each upon that which follows it.

The following is a still more striking case: Assume a cotton-mill to contain machinery demanding 400 horse-power to overcome friction, to use one fifth of a gallon of oil per hour, averaging one dollar per gallon, and giving a mean coefficient of friction of $f_1 = 0.10$, and the total cost of power to amount to \$60 per horse-power per year of 3000 working hours. Then $b = 80$, and

$$K_1 = 0.20 \times 1.00 + 80 \times 0.10 = \$8.20 \text{ per hour.}$$

If a change of oil is made, and $k_2 = 0.25$, $q_2 = 0.3$, and $f_2 = 0.15$, as may readily occur, the cost per hour is

$$K_2 = 0.25 \times 0.3 + 80 \times 0.15 = \$12.07\tfrac{1}{2},$$

and a gain of 65 per cent. in cost of oil causes a loss of about 50 per cent. in cost of wasted power; or \$375 gain per annum in expense for oil produces a net loss of over \$11,000. Such cases have probably frequently occurred. On the other hand, it is sometimes found that the cheaper oil is also that best suited to the work, and a gain is effected both in cost of oil and in expense of power.

In illustration of the application of the method just described to railroad practice, assume an oil to be used costing \$0.35 per gallon, and giving a mean coefficient $f_1 = 0.01$, the cost of work and of wear, and of that part of the fuel used on the engine, in overcoming the resistance of lubricated surfaces, which may be taken as two thirds the whole quantity burned, for example, to be \$0.20 per mile, and the quantity of oil used per mile to be 0.02 gallon.

Then the total expense per train-mile to be charged to the lost work of friction is (Eq. 13)

$$K_1 = k_1q_1 + df_1 = 0.25 \times 0.02 + 20 \times 0.01 = \$0.20\tfrac{1}{2},$$

as since $df_1 = 0.20$, $d = \dfrac{0.20}{f_1} = \$20.$

Oils causing serious wear should always be avoided, however, and cases of such wear may be left out of the account.*

Were it proposed to use an oil costing $k_2 = \$0.10$ per gallon, at the rate of $q_2 = 0.04$ gallon per mile, with a value of $f_2 = 0.02$, the cost would be

$$K_2 = k_2 q_2 + df_2 = 0.10 \times 0.04 + 20 \times 0.02 = \$0.404;$$

$$K_1 - K_2 = -\$0.199,$$

while the saving in cost of oil would be

$$k_1 q_1 - k_2 q_2 = 0.005 - 0.004 = \$0.001.$$

Saving one mill in buying oil, the amount lost on the coal account would be 20 mills, or twenty times that "saving." The apparent gain of 20 per cent. in cost of oil is enormously overbalanced by the increase of 100 per cent. in other expenses of overcoming of the friction of lubricated parts. All these figures will vary greatly for different cases; but the general conclusion remains as already stated—the relative cost of good lubricants is a comparatively unimportant matter.

Pure lard-oil would probably be best here taken as a standard for comparison.

The experiment was recently tried, on one of the great "trunk-lines" in the United States, of using pure lard-oil in summer and the best of sperm-oil in winter on freight-trains, employing one person to attend simply to their lubrication. The number of cars which could be hauled by each engine was thus increased about 10 per cent., and much greater regularity of service was secured. The saving effected in cost of transportation was sufficient to pay double the total cost of oil used and labor employed. In another case in which 50 per cent. more was paid for one oil than for another, the higher-priced oil was found very much the cheaper, on the score of saving the expense of hot journals alone.

154. **The Conclusions** to be drawn from the preceding in-

* In some cases, using crude and black petroleums, the cost of wear is but little less important than that of power.

vestigation are obvious:—The art of economical employment of lubricants consists mainly in the determination of their adaptation to specific purposes, and in the application to each machine—or to each part of a machine in which pressures on lubricated surfaces of widely differing amounts are found—of precisely that quality of unguent which is best adapted to that particular place, and, above all, applying it in the best possible way.

It is uneconomical to use a spindle-oil for the crank-pin of a steam-engine, or for the pivot of a heavy swing-bridge; to apply an engine-oil to a sewing-machine, or light machinery-oil to the journal of a railway-train. In a cotton-mill or other large manufacturing establishment, the parts of the engine, its steam-cylinder, guides, and connecting-rod journals, the heavy and the light line-shafting and the counter-shafting, as well as the several kinds and the several parts of the working machinery, may often be found to be best lubricated with different oils.

The price of lubricants is usually a matter of little interest to the user except when oils of substantially the same quality are to be compared; and whatever may be the price, an oil or a method of lubrication producing serious wear should not be used at all.

The determination of the qualities of the several grades of lubricants obtainable in the market must usually be made by the use of a good form of lubricant-testing machine, and should include a determination of wear of rubbing parts. No difficulty need be experienced in this investigation in determining the friction and endurance of any oil under specified and obtainable conditions; but it may often happen that serious difficulty may be found in the attempt to identify the precise conditions of application, or to measure the wear of journal and bearing.

It is important that this method should be applied to each department, and in each application of the lubricant in every establishment, and the relative cost of power saved, and of lubricant expended, be thus ascertained. When the market shall have finally become so well settled that prices of good oils have a direct and stable relation to their intrinsic qualities

and to the demand, this method of investigation will lead to a definite policy in every case in the purchase of lubricants.

One of the important deductions from what has preceded is the conclusion that for any given case of application the principles here developed, coupled with a correct system of test, will enable the consumer often to secure, by experimental mixing of oils, precisely that combination of qualities which best suits the conditions given. The Author has sometimes found this process to yield economical results of great financial importance.

The use of the testing-machine to determine the relative friction-reducing power and wear, and the endurance of oils as data for use in the solution of the commercial problem, will often be found to involve some difficulties. These difficulties arise, however, not from faults of the method, but from the exceedingly great uncertainty often existing as to whether the conditions of test are precisely those of use. A good testing-machine may be relied upon, if properly handled, to give accurate data; but it can rarely be made equally certain that the same conditions can be permanently retained when the lubricant is put in service. Satisfactory approximations may, however, readily be secured with careful supervision and ordinary skill, for all cases in which the machinery is well proportioned, in good order, and well cared for.

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